12-09-99

A

ATTORNEY DOCKET NO.
065113.0116

PATENT APPLICATION

APPLICATION FOR U.S. PATENT UNDER 37 C.F.R. § 1.53(b)
TRANSMITTAL FORM

Box Patent Application
ASSISTANT COMMISSIONER FOR PATENTS
Washington, D.C. 20231

Sir:

Transmitted herewith for filing is the patent application of:

Inventor or Application Identifier: **Mark E. Holzbach**

Entitled: **DYNAMIC SCALABLE FULL-PARALLAX THREE-DIMENSIONAL ELECTRONIC DISPLAY**

Enclosed are:

_X_ Specification, Claims and Abstract (_45_ Total Pages)
_X_ Drawing(s) (_6_ Total Sheet(s) of _X_ Formal___ Informal)
_X_ Combined Declaration and Power of Attorney
(_4_ Total Pages)
_X_ Newly executed (original or copy)
____ Copy from a prior application
(for continuation/divisional only)

_X_ Information Disclosure Statement (IDS) PTO-1449
_X_ Copies of IDS Citations.

___ Preliminary Amendment
_X_ Certificate of Mailing
_X_ Return Receipt Postcard
___ Other

Applicant is:
___ Large Entity
_X_ Small Entity
_X_ Small Entity Statement enclosed
___ Small Entity Statement filed in prior application.
Status still proper and desired.

AUS01:189240.1

PATENT APPLICATION

_X_ The accompanying application claims the benefit of U.S. provisional patent application Serial No. 60,111,906 filed December 10, 1998.

FEE CALCULATION					FEE
	Number		Number Extra	Rate	Basic Fee $ 380.00
Total Claims:	32	-20 =	12	X $ 9 =	$ 108.00
Independent Claims	4	- 3 =	1	X $39 =	$ 39.00
				TOTAL FILING FEE =	$ 527.00

_X_ Enclosed is a check in the amount of $527.00 to satisfy filing fee requirements under 37 C.F.R. § 1.16. Please charge any additional fees or credit any overpayment to Deposit Account No. 02-0384 of BAKER & BOTTS, L.L.P. **A duplicate copy of this sheet is enclosed.**

Respectfully submitted,
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ATTORNEY DOCKET NO.
065113.0116

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of: Mark E. Holzbach

Date Filed: December 8, 1999

Title: **DYNAMIC SCALABLE FULL-PARALLAX THREE-DIMENSIONAL ELECTRONIC DISPLAY**

Box Patent Application
Honorable Assistant Commissioner
of Patents
Washington, D.C. 20231

Dear Sir:

CERTIFICATE OF MAILING BY EXPRESS MAIL

I hereby certify that the attached Transmittal, Patent Application, Declaration and Power of Attorney, Information Disclosure Statement, Verified Statement Claiming Small Entity Status and Formal Drawings are being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 C.F.R. 1.10 on this 8th day of December, 1999, and is addressed to Box Patent Application, the Assistant Commissioner of Patents, Washington, D.C. 20231.

Matthew Beeter

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No. EL 239 242 459 US
Attorney's Docket: 065113.0116

AUS01:189248.1

Filed or Issued: Attorney's Docket: 065113.0116
Title: Dynamic Scalable Full-Parallax Three-Dimensional Electronic Display

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) & 1.27(c)) -- SMALL BUSINESS CONCERN

I hereby declare that I am an official of the small business concern empowered to act on behalf of the concern identified below:

Name of Small Business Concern: Zebra Imaging, Inc.
Address of Small Business Concern: 1406 Three Points Road
Pflugerville, Texas 78660

I hereby declare that the above-identified small business concern qualifies as a small business concern as defined in 13 CFR 121.12, and reproduced in 37 CFR 1.9(d), for purposes of paying reduced fees to the United States Patent and Trademark Office, in that the number of employees of the concern, including those of its affiliates, does not exceed 500 persons. For purposes of this statement, (1) the number of employees of the business concern is the average over the previous fiscal year of the concern of the persons employed on a full-time, part-time or temporary basis during each of the pay periods of the fiscal year, and (2) concerns are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third party or parties controls or has the power to control both.

I hereby declare that rights under contract or law have been conveyed to and remain with the small business concern identified above with regard to the invention, entitled**Dynamic Scalable Full-Parallax Three-Dimensional Electronic Display** by inventor Mark E. Holzbach described in the specification filed herewith.

If the rights held by the above-identified small business concern are not exclusive, each individual, concern or organization having rights in the invention is listed below, and no rights to the invention are held by any person, other than the inventor, who would not qualify as an independent inventor under 37 CFR 1.9(c) if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d), or a nonprofit organization under 37 CFR 1.9(e):

NONE

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or my maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b)).

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

Name of Person Signing: Mark E. Holzbach
Title of Person if other than owner: Vice President
Address of Person Signing: Zebra Imaging, Inc.
1406 Three Points Road
Pflugerville, Texas 78660

Signature: Mark E. Holzbach

Date: 7 December 1999

AUS01:154571.1

U.S. DEPARTMENT OF DEFENSE

SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
PROPOSAL COVER SHEET

Failure to fill in all appropriate spaces may cause your proposal to be disqualified

TOPIC NUMBER: A96-033

PROPOSAL TITLE: Dynamic Scalable Full-Parallax 3D Electronic Dis

FIRM NAME: Group MAAX, Incorporated

MAIL ADDRESS: 1302 Sul Ross

CITY: Houston STATE: TX ZIP: 77006

PROPOSED COST: $98,900 PHASE I OR II: I PROPOSAL PROPOSED DURATION: 6 IN MONTHS

BUSINESS CERTIFICATION:

	YES	NO
► Are you a small business as described in paragraph 2.2?	X	
► Are you a minority or small disadvantaged business as defined in paragraph 2.3? (Collected for statistical purposes only)		X
► Are you a woman-owned small business as described in paragraph 2.4? (Collected for statistical purposes only)		X
► Have you submitted proposals or received awards containing a significant amount of essentially equivalent work under other DoD or federal program solicitations? If yes, list the name(s) of the agency or DoD component, submission date, and Topic Number in the spaces below.		X

► Number of employees including all affiliates (average for preceding 12 months): 2

PROJECT MANAGER/PRINCIPAL INVESTIGATOR	CORPORATE OFFICIAL (BUSINESS)
NAME: Mark Holzbach	NAME: Alejandro Ferdman
TITLE: President	TITLE: CEO
TELEPHONE: (713) 529-6229	TELEPHONE: (713) 529-6229

For any purpose other than to evaluate the proposal, this data except Appendix A and B shall not be disclosed outside the Government and shall not be duplicated, used or disclosed in whole or in part, provided that if a contract is awarded to this proposer as a result of or in connection with the submission of this data, the Government shall have the right to duplicate, use or disclose the data to the extent provided in the funding agreement. This restriction does not limit the Government's right to use information contained in the data if it is obtained from another source without restriction. The data subject to this restriction is contained on the pages of the proposal listed on the line below.

PROPRIETARY INFORMATION: N/A

Mark Holzbach	6/28/96	Alejandro Ferdman	6/28/96
SIGNATURE OF PRINCIPAL INVESTIGATOR	DATE	SIGNATURE OF CORPORATE BUSINESS OFFICIAL	DATE

Nothing on this page is classified or proprietary information/data

U.S DEPARTMENT OF DEFENSE

SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
PROPOSAL COVER SHEET

Failure to fill in all appropriate
spaces may cause your proposal to be disqualified

TOPIC NUMBER: A96-033

PROPOSAL TITLE: Dynamic Scalable Full-Parallax 3D Electronic Display

FIRM NAME: Group MAAX, Incorporated

PHASE I or II PROPOSAL: I

Technical Abstract (Limit your abstract to 200 words with no classified or proprietary information/data.)

Group MAAX, Inc. (GMI) proposes to develop a dynamic three-dimensional electronic screen display which is autostereoscopic (i.e., no glasses or goggles required) and displays full-parallax (i.e., outputs both vertical and horizontal scene information). The display hardware can be custom configured independently of the display software according to user preferences such as total size, pixel resolution, and cost. In contrast to stereoscopic displays which only output a single stereo image pair regardless of viewing position, this display presents a view of a scene to multiple observers which varies according to their individual viewing positions relative to the display.

An interesting optional addition to the display design is the inclusion of full-parallax image acquisition camera hardware which could share the output optics and operate virtually invisibly in parallel with the image output hardware. For example, the moving 3D image information of observers could be acquired for potential use in computer-human interface interaction, or for immediate display output (with image enhancements or modifications if desired).

The main goals of the Phase I effort will be to design the system and to prove the design concepts with a still-image display mock-up and computer simulations.

Anticipated Benefits/Potential Commercial Applications of the Research or Development.

A variety of civilian and military applications are envisioned, including: simulations, terrain imaging, reconnaissance, damage assessment, mission planning, cartography, geoscience, seismic research, medical imagery, mechanical and electrical engineering, product design, visual aid, education, training, scientific visualization

List a maximum of 8 Key Words that describe the Project.

Visualization	Three-Dimensional (3D)
Electronic	Display
Spatial	Design
Billboard	Screen

1.0 IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR OPPORTUNITY

The use of the computer to assist in 3D information design, visualization, and analysis is revolutionizing the communication of 3D information, especially through the emergence of the "virtual reality" paradigm. At present people can interactively experience 3D information using a computer interface which usually requires wearing special glasses or a helmet incorporating goggles. These kinds of solutions are problematic in their unnatural obtrusiveness and difficulty in the simultaneous participation of a group or large audience. There is a real need to develop 3D display technologies which are well-tailored to the human visual system in characteristics such as resolution and in ergonomic ease of use. Autostereoscopic displays which can present 3D information to an individual or group without requiring observers to wear special goggles or glasses are the logical next step in computer-mediated 3D communications.

The fly's-eye lens sheet technique developed decades ago using optics and photographic technology ago possesses many desirable qualities for three-dimensional display such as autostereoscopy, high-resolution, full-color, high light efficiency (brightness), full-parallax (both horizontal and vertical depth information), and wide viewing angle (up to about 45 degrees). It consists of a two-dimensional array of low f-number lenslets which is positioned in front of an array of 2D images which is projected into space. The sum of all the rays of light projected from all the lenslets approximates the directions and intensities of the light rays as if they were coming from a real 3D object or scene.

The fly's-eye lens sheet is similar in principle to lenticular lens sheets which are two-dimensional arrays of semi-cylindrical lenslets which can be used in creating 3D images with horizontal parallax only. Such lenticular images have enjoyed more popularity than fly's-eye images primarily because they are technically far easier to create. However, vertical parallax information is very important under two conditions, namely when it is desirable to view the image from a variety of distances without distortions, and when it is desirable to change one's vertical position relative to the display in order to see the object or scene from a different vertical viewpoint.

The application of lens sheet techniques to electronic displays is still in its infancy. Only lenticular methods have even been attempted, and those only with low resolution screens capable of presenting stereo-image pair views to an observer at a strictly proscribed viewing distance and head positions. A fly's-eye sheet design would be more scalable in resolution and size due to the inherently symmetrical and compact lenslets, and would also be more realistic, less distorting and easier to view than a lenticular display. Primarily due to the cost of assembling thousands of lenslet "pixel" elements, each of which must have an electronic 2D image display behind it, and an image production and distribution system which presents the desired images behind each lenslet at a desired frame rate, fly's eye techniques have not been attempted. However, because the component technologies such as miniature CRTs, LCD displays, and CCD array sensors have all recently reached an adequate level of miniaturization and developed into commodities with costs decreasing at a constant rate, now is the appropriate time to consider a fly's-eye sheet design for dynamic 3D image display.

This proposal presents a design strategy which centers around the design of a lenslet pixel module. The module is first designed for optimal viewing characteristics such as wide output angle,

balanced with practical characteristics such as robustness and ease of manufacture. A large fly's-eye display design can then be envisioned incorporating as many of the modules as necessary to satisfy a given size or element resolution requirement. This modular approach has many benefits related to image quality, flexibility, and cost. The image display software requires a resolution-independent 3D digital moving image transmission format, with a central control computer producing and distributing the appropriate image information to the display elements. In addition, CCD arrays can be incorporated into some or all of the modules in the system so that the display acts as a 3D camera array as well as a display.

2.0 PHASE I TECHNICAL OBJECTIVES

The overall goal of Phase I of this project will be to demonstrate the proof of concept of a robust and flexible system for electronic autostereoscopic displays with modular components. This proof of concept will be divided into component parts which highlight how each of the critical components of the system will operate. This work will set the stage for the Phase II objective to construct and demonstrate a working system. To achieve the Phase I goal, the following technical objectives have been identified:

Objective 1: Design of a Modular Pixel Element Structure. By achieving this objective, GMI will answer questions about the visual characteristics of the display, opto-mechanical registration, and module interconnectivity.

Objective 2: Determination of optimal signal distribution mechanism. When this objective is achieved, GMI will have a solution to the problem of efficiently distributing the 3D image information in real time to the many display pixel modules in a parallel fashion.

Objective 3: Interface design. By achieving this objective, GMI will show how the proposed display can be used in conjunction with other computer-mediated systems in fields such as medicine and engineering.

Objective 4: (Optional) Development of parallel image acquisition system.

3.0 PHASE I WORK PLAN

3. 1 Project Tasks

The objectives of the proposed Phase I project, as set forth in Section 2.0, shall be accomplished through the performance of the following tasks:

Task #1: Design fly's-eye "pixel" module structure
The optimal optical design for a module will first be determined, followed by a suitable mechanical holder design which fits together in a two-dimensional array. The size of the module structure will be determined by the smallest available 2D electronic image screens (CRT or LCD) at a reasonable cost (target: under one inch in diameter).

Task #2: Fabricate mock-ups of fly's-eye "pixel" module structure. The design in Task #1 is fabricated, substituting a photographic transparency holder and backlight in place of a miniature video screen. Enough pixel modules are fabricated to proceed with Task #3 (target: at least 10,000).

Task #3: Assemble mock-up display from mock-up modules. A mock-up display is constructed from multiple "pixels". Photographic transparencies are computer generated as test images.

Task #4: Test mock-up display optical characteristics. The display is evaluated in areas such as ease of viewing, depth reconstruction limitations, and distortions.

Task #5: Design parallel signal distribution scheme. The signal distribution system must be designed so that the display pixels are supplied with the correct information in sync at video rates.

Task #6: Write software simulation of parallel image processing and signal distribution system. The software simulation will be written in order to prove the concept.

Task #7: Analyze signal distribution software simulation.
This analysis will provide the information required for successful proposed system fabrication in Phase II.

Task #8: (Optional) Design fly's-eye "pixel" module structure with camera. The pixel module structure described in Task #1 is expanded to allow for the inclusion of an CCD sensor for digital video acquisition.

Task #9: (Optional) Expand tasks 5-7 to include image acquisition signals.

Task #10: Reporting

3.2 Performance Schedule

The tasks described in Section 3.1 will be performed in accordance with the schedule shown in Figure 3-1.

SCHEDULE TIMELINE

TASKS	**MONTHS AFTER CONTRACT INITIATION** **1 2 3 4 5 6**
1. Design Module	XXXXXX
2. Fabricate Mock-up Modules	XXXXXXXXXX
3. Assemble Mock-up Display	XXXXXXXX
4. Test Display Characteristics	XXX
5. Design Distribution Schematic	XXXXXXX
6. Write Software Simulation	XXXXXXX
7. Analyze Simulation	XXXX
7. (Optional) Camera Design	XXXX
8. (Optional) Camera Simulation	XXXX
9. Prepare Reports	XXXXXX

Figure 3-1
Performance schedule

3.3 Technical Discussion

The following technical discussion begins with a brief explanation of two similar technologies for autostereoscopic 3D image display: parallax barriers, and lenticular lens sheets. The discussion continues with an extension of the lenticular concept to a full-parallax fly's-eye lens sheet display which is the basis for this proposal. A single lenslet module of the proposed fly's-eye is described, followed by a discussion of some of the parallel signal distribution alternatives. The discussion concludes with a description of optional image acquisition hardware and software additions.

3.3.0 Introduction

The basic distinguishing characteristic of an autostereoscopic 3D display from a 2D display is that the autostereoscopic display can control both the light intensity and the light directions emanating from it whereas a 2D display only modulates the light intensity. A 2D photograph or a 2D television set is perceived as a flat surface because the image surface diffuses light indiscriminately, whereas autostereoscopic displays appear 3D because the observer's two eyes are presented with two different viewpoint-dependent images. The most natural kinds of autostereoscopic displays allow an observer to move around within a wide range of viewing positions, always presenting the correct information to the eyes.

3.3.1 Parallax Barriers

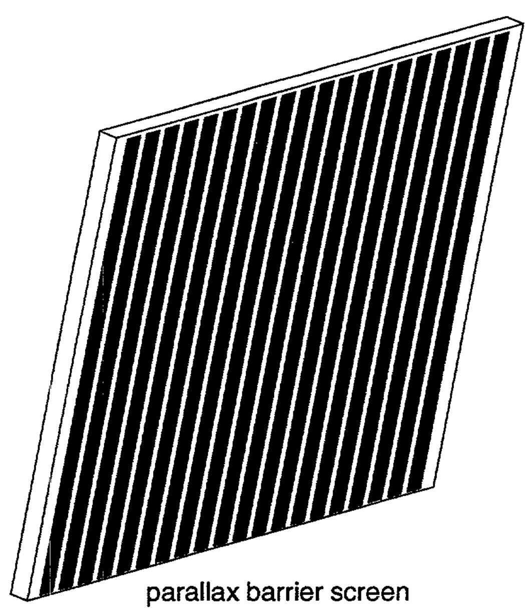


Figure 3-2

A parallax barrier display consists of a transparency with fine parallel vertical opaque lines, referred to as the parallax barrier screen, which is placed at a defined distance in front of a specially prepared picture or transparency as shown in figure 3-2 above. The specially prepared pic-

ture behind the parallax barrier screen is composed of 2D images from different viewpoints which are positioned in fine strips behind the lines of the barrier screen such that only the appropriate strips are visible from a particular viewing angle. A top down view of this display is shown in figure 3-3 below.

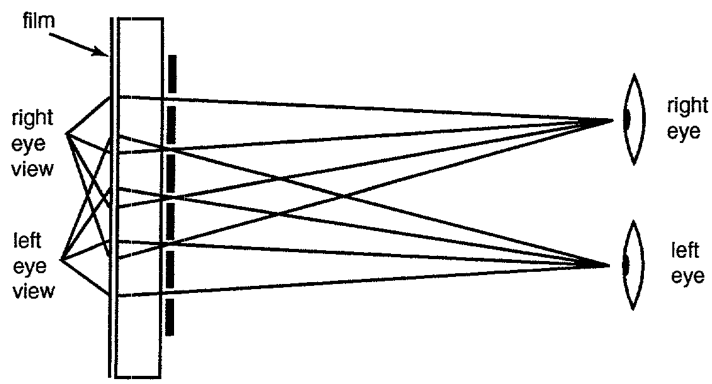


Figure 3-3

The parallax barrier screen technique has a specific set of advantages and disadvantages compared to alternative techniques. Because of the offset printing industry's need for high-resolution, high-contrast black-and-white photographic transparencies used in producing printing plates, it is possible to inexpensively produce large raster barrier screens of any desired barrier pattern up to 2400 lines-per-inch. The essential drawbacks to raster barrier screen displays are in the unavoidable darkening of the image caused by the opaque barrier strips, and by the difficulties of registering the barrier screen with the specially prepared image behind it. The use of a lightbox to back illuminate a raster barrier image can result in adequately bright images for certain viewing situations.

3.3.2 Lenticular Screen and Fly's Eye Screen Displays

The lenticular screen display is geometrically similar to the parallax barrier display. The relationship between the two display types is analogous to the relationship of a pin-hole camera to a normal convex lens camera. The lenticular screen is analogously much more light efficient than a raster barrier display.

An illustration of a lenticular screen display from the side and top down are shown in figure 3-4 below. The principle advantage of the lenticular screen display is it's superior optical efficiency or brightness compared to the parallax barrier display. Some disadvantages of the lenticular screen are in the difficulties and costs in designing and producing a good screen with minimal aberration. Another disadvantage is the problem of displaying lenticular images in outdoor situations where sunlight can be concentrated by the lenticules on the 2D image plane behind them, and cause damage. Both parallax barrier displays and lenticular displays unavoidably suffer from diffraction-limited resolution related to the width of the parallax barrier slits or the lenticules in the case of the lenticular screen.

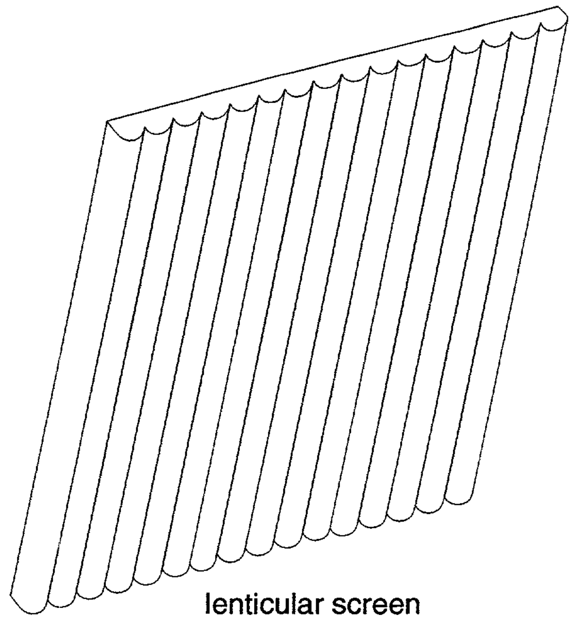


Figure 3-4

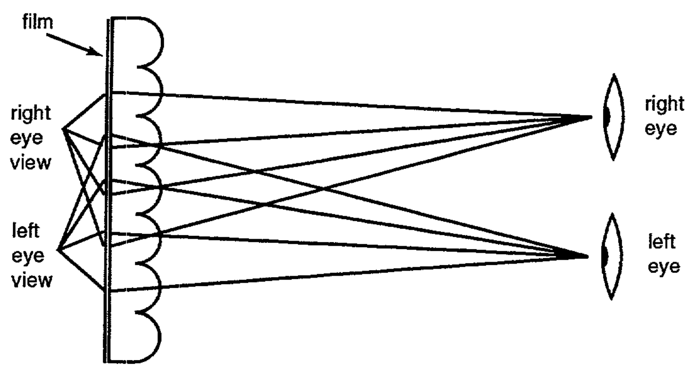


Figure 3-5

In order to display moving images, the static image screen behind the parallax barrier or behind the lenticular screen must be replaced by a moving image screen with specially prepared images composed of fine vertical strip images carefully matched to the geometrical design of the parallax barrier or lenticular screen. It is possible today to generate these special images by real-time parallel computer processing of conventional video output from a line of video cameras or from synthesized views of a computer graphics animation rendering engine. Alternatively, it is possible to optically process and combine rear-projected images using a lenticular sheet sandwich with a diffusing surface in the middle as shown in figure 3-6 below.

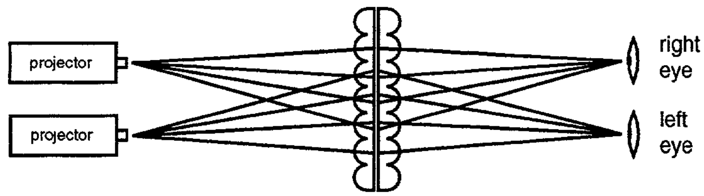


Figure 3-6

Although all the examples given above are for horizontal parallax only displays, it is straightforward to extend the concepts to full parallax. Instead of raster barrier or lenticular strips, full parallax versions would be a pinhole array and a fly's-eye lens array respectively. A fly's-eye screen is illustrated in figure 3-7 below.

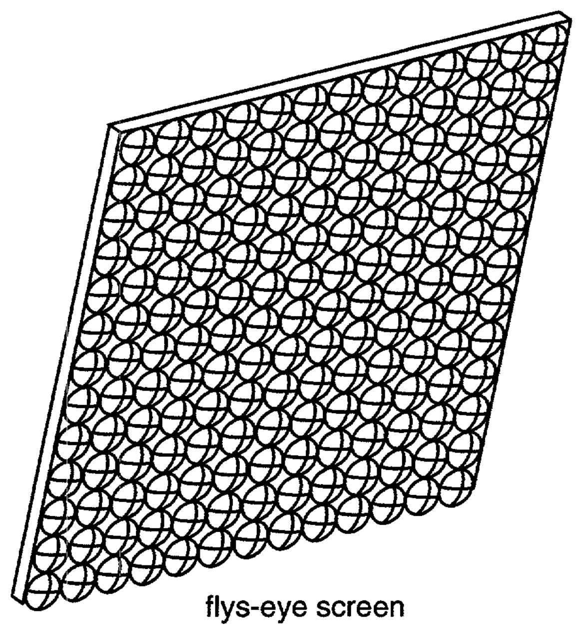


Figure 3-7

Full-parallax displays are more realistic than horizontal-parallax-only displays which is most apparent when the observer moves in a vertical direction relative to the display. Another benefit of full parallax is in the freedom it allows to view a display from any distance without observing the anamorphic distortions which are inherent in horizontal parallax only displays. The reason for these anamorphic distortions in lenticular displays is the fact that the vertical dimension of the images behind the lenticules is fixed. The relative sizes of objects in the real world change with the viewing distance. Since the vertical dimension of objects in a lenticular display is fixed, there can only be one viewing distance for which the vertical dimensions are correct.

Image information can appear both in front and behind the screen as illustrated in figure 3-8 below which shows a cross-section of a fly's-eye sheet screen where point A is imaged in front of the screen, and point B appears to be behind the screen simply due to the apparent convergence of the rays projected by the lenslets. Image points which are recorded on the 2D image source plane behind the lenslets are refracted by the lenslets and emerge in directions consistent with light from a real 3D scene.

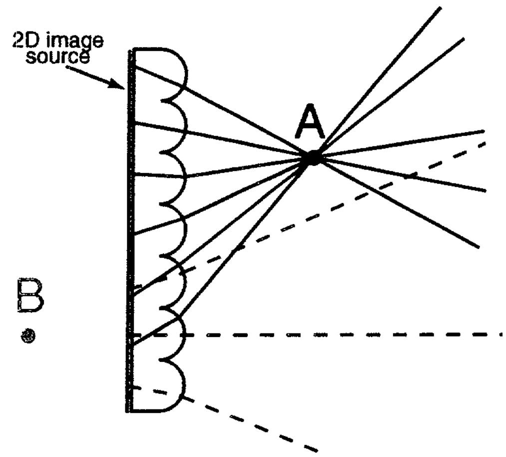


Figure 3-8

One straightforward method for creating synthetic images for a fly's-eye screen can be inferred from this figure, namely computer graphic ray tracing. Unfortunately, creating real-world images is more complicated due to a peculiar depth inversion problem which is briefly described below.

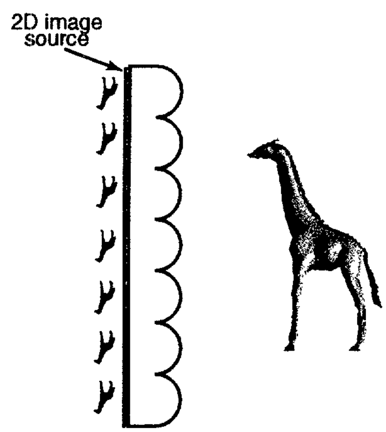


Figure 3-9

Figure 3-9 above depicts the side view of a model of a giraffe placed in front of a fly's eye sheet which has a photosensitive recording surface at its 2D source image plane. The lenslets appear to

image the giraffe as one would expect from the laws of optics, namely a small inverted image of the giraffe from the perspective of each lenslet is imaged behind it on the 2D image source plane. Since the giraffe is facing the fly's eye sheet, each lenslet images a front view of the giraffe. When the 2D source image recording is developed and placed exactly back in the position it was in during exposure, the reconstructed image of the giraffe is as the laws of optics would predict in front of the fly's eye sheet. The peculiar problem becomes evident when an observer tries to view the image from the front. When observed with a single eye from any stationary position, the giraffe appears normal, but when observed with both eyes, the 3D image is observed to be inverted in depth relative to the observer, with the giraffe's nose farther from the observer than it's ears. This problem associated with lens-sheet recordings was first noted by H. E. Ives in 1931.[2]

Ives' solution to this problem was to re-record the depth-inverted lens-sheet image in order to correct the depth. This approach was effective in correcting this problem, but it introduced additional noise in photographic processes, second-generation optical aperture-sampling artifacts, and other noise and artifacts due to compounded lenslet aberrations and diffraction. In a digital implementation the solution is much more elegant. Conventionally rendered computer graphics images or real-world images acquired with a digital camera can be systematically inverted to correct the problem. The algorithm used is a minor variation of an algorithm developed by a Group MAAX, Inc. principal, which was the subject of an entire masters' degree thesis at MIT.[3]

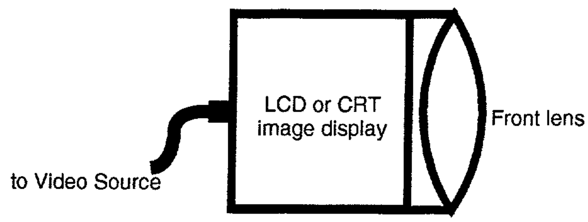
3.3.3 Fly's-Eye Lenslet Pixel Module

There are several objective characteristics for evaluating three-dimensional displays. One obvious characteristic is the two-dimensional image plane pixel resolution which is simply the number of lenslet pixel modules in a horizontal and vertical direction, and their spacing. This resolution is all one eye can appreciate from a single position in front of the display.

Another measure of the image quality of three-dimensional images is the depth resolution which depends on factors such as the lenslet size and quality and the image resolution behind each lenslet.[1] The depth resolution for a fly's-eye screen is not constant regardless of distance from the screen. Due to physical optical limits such as diffraction and the effects of lens aberrations and image misregistrations (which increase at a distance), depth resolution is best for points close to the screen (on the order of the lenslet size) and decreases with the distance from the screen. It will be possible to do a complete analysis of depth resolution during lenslet design phase of this proposal, and will be necessary in order to optimize the lenslet pixel module design to yield the best possible depth resolution.

The image information for a fly's-eye display originates on the source image plane behind the lenslets. If the source image plane is positioned at the focal length of the lenslets, a point on the source image plane behind a lenslet becomes a collimated (parallel light) beam which appears to completely fill the lenslet when observed at the correct angle relative to the lens. When the observed angle relative to the lens changes slightly, a neighboring image point from the source image plane appears to completely fill the lenslet. From this it can be seen how the size and density of neighboring image points on the source image plane is directly related to the depth resolution. A high-resolution 2D source image display, such as a miniature CRT or LCD screen, behind each lenslet would be desirable to optimize the depth resolution. However, a less-costly lower res-

olution alternative could also be achieved by positioning multiple neighboring lenslets to share dedicated regions of a single CRT or LCD screen, or sections of a diffuser back-lit by a video projection system. If the source image area positioned directly in front of one lenslet is not obstructed from the aperture of a neighboring lens, it is possible that light from the neighboring image will cross though it at a steep angle. To the observer, the combined result of this when viewing the entire display is a repeat or "flip" of the 3-D image observed at angles greater than the originally-intended viewing angle. This type of image "flip" can be considered a convenient way of allowing the display to be seen over an increased viewing angle, but it also distorts the image. Whether or not "flip" is considered an advantage or a disadvantage depends on the particular user application. If undesirable, "flip" can be eliminated by designing image blocking surfaces between the lenslets to block the source image area from neighboring lenslets from cross over.



Schematic Side View of Lenslet Module

Figure 3-10

Figure 3-10 above is a possible schematic design for a single lenslet module of the proposed display. As the illustration implies, this module design could accept an outside standard video source such as NTSC or VGA as input to a built-in LCD or CRT source image display resolutions of 640 by 480 pixels. Available displays would allow lenslet diameters under one inch. Each module would be connected to an external slave CPU with one or more video output channels, and the slave CPUs would all be controlled by a single master CPU. One illustration of a possible connectivity scheme with each slave CPU providing the video input for 3 pixel modules is shown in figure 3-11 below.

Pixel Modules

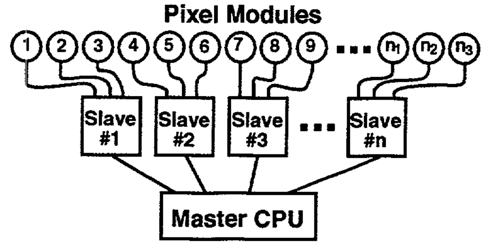


Figure 3-11

If the cost of providing an individual video source for each lenslet is too expensive, a larger flat video screen could be divided into 4 equal regions and shared among 4 pixel modules. The schematic illustration for this would resemble figure 3-11, only with each slave CPU providing the video input for 4 instead of 3 pixel modules.

In an alternative design, each module would contain an internal CPU, a communications adapter, and video display circuitry so that each module would be capable of generating its own image after being loaded with a 3D database and viewpoint information. Consumer video game player systems which are available in compact sizes and at low cost could be the basis for the electronics needed for these modules. The benefits of this massively parallel CPU approach would be in its distribution of the computation load, relaxation of signal distribution requirements, and greatly simplified connectivity as shown in figure 3-12.

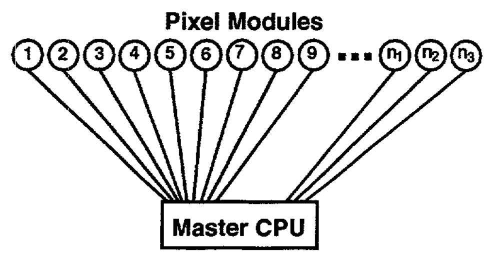


Figure 3-12

3.3.3 Pixel Module Including Camera (Optional)

Inclusion of a digital video camera inside a pixel module would open up many interesting capabilities and uses for the full-parallax display. The most likely approach to incorporate a CCD sensor in a pixel module would be to have a half-silvered mirror and additional optics to virtually superimpose both the 2D output image array plane and the 2D sensor array plane at the focal plane of the front lenslet. A consequence of this approach would be output brightness attenuation, and because of the increased bulk, the pixel module engineering to optimize pixel packing density would be non-trivial.

The integration of a 3D camera array into the display would obviously allow for full-parallax 3D image information of objects, scenes, and people to be easily acquired. This rich level of 3D data has many potential military and civilian applications such as object measurement, VR simulation source imagery, medical diagnostic information acquisition, and damage assessment information to name a few. Because the information could be acquired as moving images in real-time, clearly it could be used as the basis for virtual-reality computer-human interaction. For example, multiple human observers could have simulated computer-graphic objects tracking their moving bodies in real time. Perhaps some observers could have their images appear on the display in real time, while other observers choose to remain invisible.

4.0 RELATED WORK
4. 1 Related Work by Others

There are several other entities involved in developing raster barrier and lenticular electronic displays. Most of the efforts are being undertaken by institutions abroad such as Sanyo Electric Corp.[6] and NHK Broadcasting in Japan [8], Philips in the Netherlands [7], and by the Heinrich Hertz Institute [5] in Germany. One other American company, Dimensional Technologies, Inc.[4]

is working at making autostereoscopic screen displays primarily for remote sensing applications. Most of these (and all which are commercially available) are stereo-pair only video displays. Although these displays are autostereoscopic, they cannot be easily viewed by multiple observers because all proper viewing positions are defined with narrow tolerances. Even a single observer soon tires after using any of these displays because of the strain of continuously positioning one's head and holding it in place. The largest size display is the 70" diagonal lenticular screen from Sanyo Electric Corp.

4.2.3 Company Background

Group MAAX, Inc. was established in 1996 with the mission to take advantage of the burgeoning market for computer-mediated communications and information presentation by developing new computer and 3D-related technologies. The two GMI team principals both have exceptionally strong technical backgrounds appropriate to this opportunity. With close ties to the MIT Media Lab, and business connections worldwide, GMI is in an excellent position to spinoff and commercialize its advanced and unique technical innovations.

5.0 RELATIONSHIP WITH FUTURE RESEARCH OR RESEARCH AND DEVELOPMENT

Phase I of this project lays the detailed groundwork for the Phase II design and production of a scalable full-parallax autostereoscopic electronic display, as described in Section 1.0 of this proposal. Group MAAX, Incorporated plans to see this project through its commercial development stages.

All the tasks for Phase I are groundwork tasks of absolute vital importance to the further Phase II development and subsequent commercialization of the system. For example, as described in section 3.1, tasks 1 through 4 deal with the pixel module design which is vital to Phase II and a proof of concept demonstration which is very important both to confirm the project going forward and to potentially attract outside funding to assist in commercialization. Tasks 5-7 design and simulation of the image distribution system will provide information which is critical in order to proceed with Phase II construction of a prototype with adequate performance for interactive use.

6.0 POTENTIAL POST APPLICATIONS

The number of potential applications which could use a large 3D display such as the one described in this proposal is vast. We expect that many people with VR applications would be potentially interested in this technology because of its unique aspects and capabilities. Some potential post applications include mission planning, reconnaissance, damage assessment, scene analysis, education, training, simulations, mechanical and electrical engineering, cartography & terrain imaging, geoscience, seismic research, medical imagery, product design, architecture, space planning, advertising, scientific visualization and teleconferencing.

Group MAAX, Inc. intends to vigorously pursue follow-on funding and form strategic partnerships in order to commercialize the proposed system.

7.0 KEY PERSONNEL

7. 1 Principal Investigator: Mark Holzbach

Mark Holzbach, President, Group MAAX, Inc., received his B.S. in Astrophysics and German Literature from Middlebury College, and his M.S. at MIT for his holography work in the Spatial Imaging Group of the MIT Media Laboratory. Among the first graduate students working under Professor Stephen Benton at the inception of the MIT Media Lab, Mr. Holzbach wrote his Masters' thesis on his invention of basic computer graphic predistortion techniques necessary for practical one-step holographic stereogram production. Mr. Holzbach has spent most the years following his graduation from MIT in Japan. From 1990-1995 he served on the board of directors of Asaca Corporation of Tokyo Japan, a manufacturer of specialized video equipment and computer mass data storage robotic autochangers. Mr. Holzbach is an expert on autostereoscopic display technologies with several publications to his credit and was often asked to lecture on the topic in Japan. He has been invited to teach a course on display technologies at Rice University in the fall together with Alejandro Ferdman.

7.2 Other Key Personnel: Alejandro Ferdman

Alejandro Ferdman, Chief Executive Officer, Group MAAX, Inc., received his B.A. (Summa Cum Laude) in Computer Science from Brandeis University (junior year was spent at the Computer Science Department of the University of Edinburgh, Scotland), and his M.S. at MIT from the Computer Graphics and Animation Research Group of the MIT Media Lab. Mr. Ferdman was involved in pioneering inverse kinematics work supported by a National Science Foundation Fellowship, which became his Masters' thesis. During his graduate student tenure at the MIT Media Lab, Mr. Ferdman and another student produced the world's first full-color computer graphic holographic stereogram image of an imaginary desert landscape scene. Mr. Ferdman's talents extend into management; as President of a 50-employee general contracting company in Puerto Rico from 1986-1994 he doubled it's volume. He has been invited to teach a course on display technologies at Rice University in the fall together with Mark Holzbach.

8.0 FACILITIES/EQUIPMENT

Group MAAX, Inc.'s Houston office houses the company's software development resources which include the following computer systems:

* Silicon Graphics IRIS Indigo running IRIX 4.2
* Power Macintosh 9500/132 running MacOS 7.5.3
* Power Macintosh 6100/60AV running MacOS 7.5.3
* Hymco IBM Compatible 133 MHz Pentium running Windows '95

The Group MAAX, Inc. Houston facilities are centrally located in the city, close to Rice University.

The above facilities meet environmental laws and regulations of federal, state (Texas) and local governments for, but not limited to, the following: airborne emissions, waterborne effluents, external radiation levels, outdoor noise, solid and bulk waste disposal practices, and handling and storage of toxic and hazardous materials.

9.0 PRIOR, CURRENT OR PENDING SUPPORT

No prior, current or pending support for proposed work.

10.0 REFERENCES

1) Takanori Okoshi, "Three-Dimensional Imaging Techniques," Academic Press, New York, 1976

2) H.E. Ives, "Optical Properties of a Lippmann Lenticulated Sheet," J. Opt. Soc. Amer. 21, March, 1931

3) M. Holzbach, "Three-Dimensional Image Processing for Synthetic Holographic Stereograms," MIT Masters' Thesis, September, 1986

4) J. B. Eichenlaub, Dimensional Technologies, Inc., "3D Without Glasses," Information Display Magazine, pp. 9-12

5) R. Boerner, "Design of Lenticular Screens and Its Application to Various 3D Systems," Proceedings of the International Symposium on Three Dimensional Image Technology and Arts, Tokyo, February, 1992

6) T. Okino, et. al., "New Television with 2D/3D Image Conversion Technologies," SPIE Conference 2653A, San Jose, February, 1996

7) C. van Berkel, et. al., "Multiview 3D-LCD," SPIE Conference 2653A, San Jose, February, 1996

8) H. Kusaka, "Research Activities of NHK for Three-Dimensional Images," Proceedings of the International Symposium on Three Dimensional Image Technology and Arts, Tokyo, February, 1992

APPENDIX C

GROUP MAAX, INCORPORATED
1302 SUL ROSS
HOUSTON, TX 77006

TOPIC NO: 96-033
AGENCY: ARMY

TOPIC TITLE: DISPLAY DEVICE DEVELOPMENT

PROP. TITLE: DYNAMIC SCALABLE FULL-PARALLAX 3D ELECTRONIC DISPLAY

TOTAL AMOUNT PROPOSED: $98,900

CONTRACT PRICING PROPOSAL - - SIX MONTHS

TOTAL PROJECT SUMMARY

01. Direct Labor	Hours	Rate $ / hour	Costs
Mark Holzbach:Principal Investigator	300	$70	$21,000
Alex Ferdman:Principal Scientist	300	$70	$21,000
TOTAL DIRECT LABOR			$42,000
Overhead (25% of direct labor)			$10,500
Materials & Equipment			$33,500
TOTAL DIRECT COST and OVERHEAD			$86,000
G & A Expenses (15% of above)			$12,900
TOTAL COST			$98,900
TOTAL FEE (100% of above)			$98,900
TOTAL ESTIMATED PROJECT BUDGET			$98,900

NOTES:

A. MATERIALS and EQUIPMENT

50 pixel square display (50x50 = 2,500 pixel modules) with photographic slides for proof of concept:

slides $ .25 each
lenslet $ 6.75 each
housing $ 5.60 each
TOTAL $12.60 each x 2,500 = $31,500 + lighting $2,000 = $33,500

Alex Ferdman

____DATE: 6-28-96

Signature: Alejandro Ferdman, CEO

ANSWERS TO APPENDIX C QUESTIONS:

21a,b & c: No
22: Firm-fixed price.

DYNAMIC SCALABLE FULL-PARALLAX THREE-DIMENSIONAL ELECTRONIC DISPLAY

RELATED PATENT APPLICATION

This application claims the benefit of U.S. Provisional Application No. 60/111,906, filed December 10, 1998 and entitled "Dynamic Scalable Full-Parallax Three-Dimensional Electronic Display".

TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to large scale autostereoscopic displays and, more particularly, to a system and method which uses lenslet pixel modules to provide a dynamic, scalable, full-parallax three-dimensional electronic display.

BACKGROUND OF THE INVENTION

The use of computers to assist in three-dimensional (3D) information design, visualization, and analysis is revolutionizing the communication of 3D information, especially through the emergence of the "virtual reality" paradigm. At present people can interactively experience 3D information using a computer interface which usually requires wearing special glasses or a helmet incorporating goggles. These kinds of solutions are problematic in their unnatural obtrusiveness and difficulty in simultaneous participation of a group or large audience.

Fly's eye lens sheets and related techniques were developed decades ago using optics and photographic technology. Fly's eye lens sheets possess many desirable qualities for use in 3D display such as autostereoscopy, high-resolution, full-color, high light efficiency (brightness), full-parallax (both horizontal and vertical depth information), and wide viewing angle (up to about forty-five (45) degrees). Such displays often include a fly's eye lens sheet having a two-dimensional array of low f-number lenslets which are positioned in front of one or more two-dimensional (2D) images. The 2D image or images are projected into space by the fly's eye lens sheet. The sum of all rays of light projected from the lenslets approximates the directions and intensities of

light rays coming from a real 3D object or scene corresponding with the 2D image or images.

Fly's eye lens sheets are often considered functionally analogous to lenticular lens sheets which are typically 2D arrays of semi-cylindrical lenslets used in creating 3D images with horizontal parallax only. The resulting lenticular displays have enjoyed more popularity than displays using fly's eye lens sheets primarily because lenticular lens sheets are technically easier to create. The application of lens sheet techniques to electronic displays is still in an early development stage. Typically, only lenticular lens sheet methods have even been commercially attempted, and only with relatively low resolution displays capable of presenting stereo-image pair views to an observer at a strictly proscribed viewing distance and head positions. Large 3D electronic displays having fly's eye lens sheets have generally not been considered due to associated costs and difficulty in manufacture and assembly of the display.

There has been previous discussions about developing an optical input/output system having "projection pixels" with one or more "camera pixels" interleaved within the array of projection pixels. See for example "The I/O Bulb And The Luminous Room" prepared by John Stephen Underkoffler published during February 1999 as partial

fulfillment of the requirements for a doctoral degree from Massachuset Institute of Technology.

SUMMARY OF THE INVENTION

In accordance with teachings of the present invention a system and method are provided to produce a scalable, 3D electronic display having a plurality of lenslet pixel modules. For some applications the display will produce a full parallax image. However, a 3D electronic display incorporating teaching of the present invention may be used to produce horizontal parallax only or vertical parallax only images. Each lenslet pixel module is designed in accordance with teaching of the present invention for optimal viewing characteristics such as wide output balanced with practical characteristics such as robustness and ease of manufacture. For one application, a large electronic display may be formed with as many of lenslet pixel modules as necessary to satisfy a given size or element resolution requirement. Fly's eye lens sheets may be used to form part of each lenslet pixel module. The modular approach of the present invention has many benefits related to image quality, flexibility, and reduced cost.

One aspect of the present invention preferably includes using image display software within an electronic display to provide an independent 3D digital moving image transmission format along with a central control computer for producing and distributing

appropriate image information to associated lenslet pixel modules. In addition, a sensor such as a charge coupled device (CCD) can be incorporated into some or all of the lenslet pixel modules so that the resulting 3D electronic display may function as a 3D camera as well as a 3D display. For other applications, the 3D display may include an array of sensor elements interspersed with an array of lenslet pixel modules as opposed to combining sensor elements within respective lenslet pixel modules. For still other applications, there may be a combination of sensor/projector elements, sensor-only elements and projector-only elements as desired for each specific electronic display.

Technical benefits of the present invention include providing autostereoscopic displays which are tailored to the human visual system in characteristics such as resolution and ergonomic ease of use. Technical benefits of such autostereoscopic displays also include presenting 3D information to an individual or group of observers using computer mediated 3D communications in accordance with teachings of the present invention without requiring each observer to wear special goggles or glasses.

Forming an electronic display using one or more fly's eye lens sheets in accordance with teachings of the present invention provides vertical parallax information which may be very important when it is desirable to view an image from a variety of distances without distortions

and when it is desirable to change an observer's vertical position relative to the display in order to view the associated image from different vertical positions. Fly's eye lens sheet designs are generally more scalable in resolution and size due to the inherently symmetrical and compact lenslets. Fly's eye lens sheets generally produce a more realistic, less distorting and easier to view 3D image as compared to a lenticular type display.

The present invention allows using high resolution 2D image sources such as miniature cathode ray tubes (CRTS), liquid crystal displays (LCDs), digital micro device (DMD) mirrors, microelectronicmechanical systems (MEMS) and charge coupled device (CCD) sensors to provide a 2D image at each lenslet pixel module of a 3D electronic display at a reasonable cost. A wide variety of light valves and/or light modulators may be satisfactorily used to provide the desired 2D image preferably in a digital format to each lenslet pixel module. Some of these images sources may be low resolution.

Computer control systems and software may be used to provide an image production and distribution system which presents the desired 2D image behind each lenslet pixel module at a desired frame rate. Miniature CRTS, LCDs, CCD sensors, and other high resolution light valves and light modulators have all recently reached an adequate level of miniaturization and developed into commodities

with costs decreasing at a constant rate such that a fly's eye lens sheet and multiple high resolution 2D image sources may be combined to form a dynamic 3D image display.

Other technical benefits and advantages will be apparent to one of ordinary skill in the art after reviewing the specification, drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention and advantages thereof may be acquired by reviewing the following descriptions taken in conjunction with the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIGURE 1 is a schematic drawing showing an isometric view of a portion of a parallax barrier screen display;

FIGURE 2 is a schematic drawing showing a plan view of the parallax barrier screen display of FIGURE 1;

FIGURE 3 is a schematic drawing showing an isometric view of a portion of a lenticular screen display;

FIGURE 4 is a schematic drawing showing a plan view of the lenticular screen display of FIGURE 3;

FIGURE 5 is a schematic drawing showing a plan view of another lenticular screen display having a first lenticular lens sheet and a second lenticular lens sheet with a diffused surface disposed therebetween;

FIGURE 6 is a schematic drawing showing an isometric view of a display screen formed in part by a fly's eye lens sheet;

FIGURE 7 is a schematic drawing showing a plan view of the display screen of FIGURE 6;

FIGURE 8 is a schematic drawing showing a side view of a fly's eye lens sheet used to record an image on photosensitive recording material;

FIGURE 9 is a schematic drawing with portions broken away of a single lenslet pixel module incorporating teachings of the present invention for use in a 3D electronic display;

FIGURE 10 is a schematic drawing with portions broken away of a display system having a multiple lenslet pixel modules incorporating teachings of the present invention;

FIGURE 11 is a schematic drawing with portions broken away of another display system having multiple lenslet pixel modules incorporating teachings of the present invention;

FIGURE 12 is a schematic drawing showing a plan view with portions broken away of a lenslet pixel module having both a projector element and a sensor element;

FIGURE 13 is a schematic drawing with portions broken away showing still another display system having a selected number of lenslet pixel modules with respective projector elements and a selected number of lenslet pixel modules with respective sensor elements in accordance with teachings with the present inventions;

FIGURE 14 is a schematic drawing with portions broken away of a display system having multiple lenslet pixel modules which include both projector elements and sensor elements incorporating teachings of the present invention; and

FIGURE 15 is a schematic drawing with portions broken away showing still another display system having a selected number of lenslet pixel modules with high resolution and low resolution sensor elements and a selected number of lenslet pixel modules with a high resolution image display elements and low resolution image display elements.

DETAILED DESCRIPTION OF THE INVENTION

Preferred embodiments of the present invention and its advantages are best understood by reference to FIGURES 1-15 of the drawings, like numerals being used for like and corresponding parts of the various drawings.

The following written description discusses various embodiments of a scalable, full-parallax 3D electronic display formed in accordance with teachings of the present invention. The description begins with a brief explanation of two similar technologies for providing autostereoscopic 3D image displays: parallax barrier displays and lenticular lens sheet displays. The description includes a comparison of lenticular lens sheet displays with fly's eye lens sheet displays and the benefits resulting using a fly's eye lens sheet to form a display in accordance with teachings of the present invention. A single lenslet pixel module having a fly's eye lens is described, followed by a discussion of some parallel signal distribution techniques to enhance the resulting 3D electronic display. The description concludes with examples of optional image acquisition hardware and software modifications.

Pixel is an abbreviation for picture element. For purposes of describing various features of the present invention, the term "3D pixel" will be used to refer to the smallest part of an electronically coded 3D graphic or 3D picture image. Pixel may also be used to refer to

the smallest addressable element in an electronic display. Conventional LCD Projectors and CCD sensors typically have an array of 2D pixels. The present invention provides an electronic display which produces a 3D image having 3D pixels.

The terms "lenslet pixel module" and "lenslet pixel modules" are used to describe various components such as high resolution and low resolution 2D image sources, fly's eye lenslets and/or a sensor elements which may be combined in accordance with teachings of the present invention to form a 3D pixel in a resulting autostereoscopic image and/or detect a portion of a real 3D object. Various features of the present invention may be described with respect to "projector pixels" which form a portion of an electronic display and "sensor pixels" which detect electromagnetic radiation from one or more real 3D objects or from a scene adjacent to the electronic display.

The terms "projector module" or "projector modules" are used to refer to lenslet pixel modules which form a 3D pixel in a resulting autostereoscopic image. The terms "sensor module", "detector module", "sensor modules" and "detector modules" are used to describe lenslet pixel modules which are responsive to electromagnetic radiation from a real 3D object or a real scene adjacent to an electronic display incorporating teachings of the present invention.

The term "high resolution" is used to refer to a 2D image source and to a sensor element having a 2D array of at least 1280 by 1024 pixels.

Various embodiments of the present invention will be described with respect to lens sheets and lenslets satisfactory for use in forming 3D displays incorporating teachings of the present invention may be formed from a wide variety of optically transparent materials such as plastics and glass. Lens sheets and lenslets are often formed using injection molding techniques. Commercially available optical design and fabrication methods may be used to form various components of an electronic display incorporating teachings of the present invention. Also, the selection of various optical elements, their respective locations and optical characteristics such as aperture, diameter and focal length may be determined in accordance with commercially available techniques associated with digital electronic and holographic displays.

A basic characteristic distinguishing an autostereoscopic display from a 2D display is that an autostereoscopic display can generally control both light intensity and light directions emanating therefrom whereas a 2D display only modulates light intensity. A 2D photograph or a 2D television set is perceived as a flat surface because the image surface diffuses light indiscriminately, whereas autostereoscopic displays

appear 3D because the observer's two eyes are presented with two different viewpoint-dependent images. The most natural kinds of autostereoscopic displays allow an observer to move around within a wide range of viewing positions, always presenting the correct information to the observer's eyes.

PARALLAX BARRIER DISPLAYS

FIGURES 1 and 2 are schematic diagrams showing one example of a typical parallax barrier screen display indicated generally at 20. A parallax barrier screen display such as display 20 generally includes a transparency or sheet 22 with fine parallel vertical opaque lines 24 which are placed at a defined distance in front of a specially prepared picture or film 28 as shown in FIGURE 2. Sheet 22 and opaque lines 24 cooperate with each other to form parallax barrier screen 26. Specially prepared picture or film 28 disposed adjacent to parallax barrier screen 26 generally includes 2D images (not expressly shown) from different viewpoints which are positioned in fine strips behind lines 24 of parallax barrier screen 26 such that only the appropriate strips are visible from a particular viewing angle.
FIGURE 2 is a diagram of a top down view of one embodiment of parallax barrier screen display 20.

The parallax barrier screen technique has a set of advantages and disadvantages compared to alternative

techniques. Because of the offset printing industry's need for high-resolution, high-contrast black-and-white photographic transparencies used in producing printing plates, it is possible to inexpensively produce large raster barrier screens of any desired barrier pattern up to 2400 lines-per-inch. The essential drawbacks to raster barrier screen displays are in the unavoidable darkening of the image caused by the opaque barrier strips, and by the difficulties of registering the barrier screen with the specially prepared 2D image or images disposed adjacent thereto. The use of a lightbox (not expressly shown) to back illuminate a raster barrier screen can result in adequately bright images for certain viewing situations.

<u>LENTICULAR SCREEN AND FLY'S EYE SCREEN DISPLAYS</u>

A lenticular screen display is geometrically similar to a parallax barrier screen display. The relationship between the two types of displays is analogous to the relationship of a pin-hole camera to a normal convex lens camera. A lenticular screen display is analogously much more light efficient than a parallax barrier screen display.

FIGURES 3 and 4 are schematic diagrams showing one example of a lenticular screen display indicated generally at 3D. A principle advantage of a lenticular screen display such as display 3D is its superior optical

efficiency or brightness compared to a parallax barrier display.

For the example shown in FIGURES 3 and 4 lenticular screen display 3D preferably includes lenticular lens sheet 32 have a plurality of parallel, vertical lenticules 34 form on one surface thereof. A specially prepared picture or film 38 may be disposed adjacent to lenticular lens sheet 32 opposite from lenticules 34 as shown in FIGURE 4. Picture or film 38 preferably includes one or more 2D images which will be projected from lenticular lens sheet 32 as a horizontal parallax only 3D image.

Some disadvantages of a lenticular screen display are the difficulties and costs in designing and producing a good lenticular lens sheet with minimal aberrations. Another disadvantage is the problem of displaying lenticular images in outdoor situations where sunlight may be concentrated by the associated lenticules on the 2D image plane behind the lenticules and cause damage to the picture or film having the 2D image. Both parallax barrier screen displays and lenticular screen displays unavoidably suffer from diffraction limited resolution related to the width of the parallax barrier slits or the lenticules in the case of a lenticular screen display.

In order to display moving images, the static 2D image behind the parallax barrier screen or behind the lenticular screen may be replaced by a moving image

screen or moving image source with specially prepared images composed of fine vertical strip images carefully matched to the geometrical design of the parallax barrier screen or lenticular screen. It is possible to generate these special moving images by real-time parallel computer processing of conventional video output from a line of video cameras (not expressly shown) or from synthesized views of a computer graphics animation rendering engine (not expressly shown). Alternatively, it is possible to optically process and combine rear-projected images using two or more projectors 40 and 41 along with lenticular lens sheets 42 and 43 with diffusing surface 44 disposed therebetween as shown in FIGURE 5.

Parallax barrier screen display 20 and lenticular screen display 3D are horizontal parallax only displays. These displays may be modified to full parallax displays by replacing parallax barrier sheet 22 or lenticular lens sheet 32 with a pinhole array and a fly's eye lens sheet respectively.

FIGURES 6 and 7 are schematic drawings showing one example of a typical fly's eye screen display shown generally at 50. A fly's eye screen display such as display 50 generally includes a fly's eye lens sheet 52 having an array of fly's eye lenslets 54 disposed on one surface thereof. The opposite surface of a fly's eye lens sheet 52 is preferably flat and smooth. Fly's eye

lenslets 54 may be described as generally spherical bumps.

Two-dimensional image source 58 is preferably disposed on fly's eye lens sheet 52 opposite from lenslets 54. Two-dimensional image source 58 may be a picture or film as previously described with respect to lenticular screen display 3D. For some applications 2D image source 58 may be a moving image screen or other moving image source.

Full parallax displays such as display 50 provide more realistic 3D images as compared to horizontal parallax only displays such as displays 20 and 3D. The difference is most apparent when an observer moves in a vertical direction relative to the displays. Another benefit of a full parallax display is in the freedom it allows an observer to view a display from any distance without observing the anamorphic distortions which are inherent in horizontal parallax only displays. The reason for these anamorphic distortions in lenticular displays such as display 3D is the fact that the vertical dimension of the images behind lenticules 34 is fixed. The relative sizes of objects in the real world change with the viewing distance. Since the vertical dimension of objects in lenticular display 3D is fixed, there can only be one viewing distance for which the vertical dimensions of the resulting 3D image are correct.

Image information can appear both in front and behind fly's eye screen display 50 as shown in FIGURE 7. FIGURE 7 shows a cross-section of fly's eye screen display 50 where point A is imaged in front of display 50 and point B appears to be behind display 50 simply due to the apparent convergence of the rays projected by fly's eye lenslets 54. Image points which are recorded on 2D image source 58 disposed behind lenslets 54 are refracted by lenslets 54 and emerge in directions consistent with light from a corresponding real 3D object or scene.

One method for creating synthetic 2D images for a fly's eye screen display can be inferred from FIGURE 7, namely computer graphic ray tracing. Unfortunately, creating real-world images is more complicated due to a peculiar depth inversion problem which is briefly described below.

FIGURE 8 depicts a side view of a model of a cat placed in front of fly's eye lens sheet 52. For purposes of explanation a layer of photosensitive recording material may be placed on lens sheet 52 at the surface previously occupied by 2D source image 58. Lenslets 52 appear to image the cat as one would expect from the laws of optics, namely a small inverted image of the cat from the perspective of each lenslet is imaged behind it on the photosensitive recording material at the 2D image source plane. Since the cat is facing fly's eye lens sheet 52, each lenslet 54 images a front view of the cat.

When the photosensitive recording material is developed and placed exactly back in the same position it was in during exposure, a reconstructed image of the cat will be presented, as the laws of optics would predict, in front of fly's eye lens sheet 52.

The peculiar problem becomes evident when an observer tries to view the image from the front. When observed with a single eye from any stationary position, the cat appears normal, but when observed with both eyes, the 3D image is observed to be inverted in depth relative to the observer, with the cat's nose farther from the observer than it's tail. This problem associated with lens-sheet recordings was first noted by H. E. Ives in "Optical Properties of a Lippman Lenticulated Sheet," J. Opt. Soc. Amer. 21, March, 1931.

Ives' solution to this problem was to re-record the depth-inverted lens-sheet image in order to correct the depth. This approach was effective in correcting this problem, but it introduced additional noise in photographic processes, second-generation optical aperture-sampling artifacts, and other noise and artifacts due to compounded lenslet aberrations and diffraction.

In a digital implementation the solution can be much more elegant. Conventionally rendered computer graphics images or real-world images acquired with a digital camera (not expressly shown)or other suitable sensor can

be systematically inverted to correct the problem. The algorithm used can be a variation of an algorithm developed, which was the subject of a masters' degree thesis by M. Holzbach, "Three-dimensional Image Processing for Synthetic Holographic Stereograms," MIT Master's Thesis, September, 1986.

LENSLET PIXEL MODULES

There are several objective characteristics for evaluating 3D displays. One obvious characteristic is the 2D image plane pixel resolution which is simply the number of lenslet pixel modules in a horizontal and vertical direction, and their spacing. This resolution is all one eye can appreciate from a single position in front of the display.

Another measure of image quality of 3D images is depth resolution which depends on factors such as lenslet size and quality and image resolution behind each lenslet. Depth resolution for a fly's eye screen is not constant regardless of distance from the screen. Due to physical optical limits such as diffraction and the effects of lens aberrations and image misregistrations (which increase at a distance), depth resolution is best for points close to the screen (on the order of the lenslet size) and decreases with the distance from the screen. Complete analysis of depth resolution during lenslet design phase is preferably conducted as part of

forming a 3D electronic display in accordance with teachings of the present invention to optimize lenslet pixel module design to yield the best possible depth resolution.

The image information for a fly's eye screen display originates on the source image plane behind the lenslets. If the 2D image source plane is positioned at the focal length of the lenslets, a point on the 2D image source plane behind a lenslet becomes a collimated (parallel light) beam which appears to completely fill the lenslet when observed at the correct angle relative to the lenslet. When the observed angle relative to the lenslet changes slightly, a neighboring image point from the 2D image source plane appears to completely fill the lenslet. From this it can be seen how the size and density of neighboring image points on the 2D image source plane are directly related to depth resolution.

A high resolution 2D image source, such as a miniature CRT or LCD screen, behind each lenslet is often desirable to optimize the depth resolution. However, a less-costly lower resolution alternative may also be achieved by positioning multiple neighboring lenslets to share dedicated regions of a single CRT or LCD screen, or sections of a diffuser back-lit by a video projection system (not expressly shown). As noted later in this written description, a wide variety of light valves and light modulators may be satisfactorily used with lenslet

pixel modules incorporating teachings of the present invention. Although high resolution 2D image sources are preferred, a 3D electronic display may be formed in accordance with teachings of the present invention using low resolution 2D image sources. Also, a wide variety of electromagnetic sensor and detectors may be satisfactorily used with lenslet pixel modules incorporating teachings of the present invention.

If the 2D image source positioned directly in front of one lenslet is not obstructed from the aperture of a neighboring lenslet, it is possible that light from the neighboring 2D image source will cross though it at a steep angle. To an observer, the combined result when viewing the entire display is a repeat or "flip" of the 3D image observed at angles greater than the originally intended viewing angle. This type of image "flip" can be considered a convenient way of allowing the display to be seen over an increased viewing angle, but it also distorts the image. Whether or not "flip" is considered an advantage or a disadvantage depends on the particular user application. If undesirable, "flip" can be eliminated by designing image blocking surfaces (not expressly shown)between the lenslets to block the 2D image source from neighboring lenslets from cross over.

FIGURE 9 is a schematic diagram showing one embodiment of single lenslet pixel module 70 incorporating teachings of the present invention.

Lenslet pixel module 70 preferably includes fly's eye lenslet 74 so that a 2D image may be projected from high resolution 2D image source 78 through fly's eye lenslet 74. Other types of lenslets satisfactory for use in forming a portion of a 3D image may be used. The present invention is not limited to fly's eye lenslet 74. Lenslet pixel module 70 may sometimes be referred to as a projection module or a projection pixel.

Various types of commercially available light valves and light modulators may be satisfactorily used as high resolution 2D image source 78. For the embodiment shown in FIGURE 9, high resolution 2D image source 78 may be a digital flat panel display (FPD), an LCD or CRT. Other types of high resolution 2D image sources including light emitting diodes (LED). DMD mirrors and MEMS may also be satisfactorily used to form lenslet pixel modules 70.

A plurality of lenslet pixel modules 70 may be arranged relative to each other in a generally rectangular array to provide an electronic 3D display (not expressly shown) having a resolution of 640 x 480 3D pixels. The front of such an array may look similar to display 50 in FIGURE 6. For some applications, fly's eye lenslet 74 may have a diameter less than one inch.

A standard video source (not expressly shown) shown as NTSC or VGA may be connected to high resolution 2D image source 78. For other applications, digital data may be supplied to high resolution 2D image source 78

which then converts the digital data into the desired 2D image. An important aspect of the present invention includes providing moving images or even live images to lenslet pixel modules 70.

A 3D electronic display may be formed in accordance with teachings of the present invention by using fly's eye lens sheet 52 as shown in FIGURE 6 to form a generally rectangular, flat array. For other applications lenslet pixel modules 70 may be used to form a generally curved array (not expressly shown). Lenslet pixel modules incorporating teachings of the present invention may be arranged in a wide variety of arrays and/or mosaics as desired to provide the resulting full parallax 3D image.

A plurality of high resolution 2D image sources may be coupled with respective fly's eye lenslet 54 to form the desired lenslet pixel module array. For other applications two or more lenslets 74 may share dedicated regions of the same high resolution 2D image source 78 (not expressly shown). For example a high resolution FPD may be combined with fly's eye lens sheet 52 in accordance with teachings of the present invention.

FIGURE 10 is a schematic drawing showing system 80 incorporating teachings of the present invention for presenting a scalable, full parallax autostereoscopic image. System 80 preferably includes a plurality of lenslet pixel modules 70 which may be arranged relative

to each other in a wide variety of arrays or mosaics. For one example lenslet pixel modules 70 may be arranged to form an array similar to display 50 as shown in FIGURE 6. For other applications lenslet pixel module 70 may be arranged in various geometric configurations such as concave, convex, rectangular, square or cylindrical.

System 80 also includes a plurality of slave computer processing units (CPU) 82 with one or more lenslet pixel modules 70 coupled with each slave CPU 82. Depending upon the type of light valve or light modulator used to form lenslet pixel module 70, a video output channel may be used to couple each slave CPU 82 with its associated lenslet pixel modules 70. For other applications each slave CPU 82 may have a digital connection with its associated lenslet pixel module 70. Digital data from each slave CPU 82 may be converted to the desired 2D image by high resolution 2D image source 78.

System 80 preferably includes master computer processing unit (CPU) 84 which is preferably connected with and controls the operation of each slave CPU 82. For the embodiment shown in FIGURE 10, three lenslet pixel modules 70 are coupled with each slave CPU 82. However, the number of slave CPUs, master CPUs and lenslet pixel modules may be varied in accordance with teachings with the present inventions to provide the desired scalable, full parallax autostereoscopic image.

If the cost of providing an individual 2D image source for each lenslet is too expensive, a larger FPD (not expressly shown) or a video screen (not expressly shown) may be divided into four equal regions and shared among four lenslet pixel modules 70. The schematic illustration for this would be similar to FIGURE 10, only with each slave CPU 82 providing the desired 2D image input for four lenslets pixel modules 70 instead of three lenslet pixel modules 70.

For some 3D electronic displays, each lenslet pixel module 70 may contain an internal CPU, a communications adapter, and video display circuitry so that each lenslet pixel module 70 may generate its own 2D image after being loaded with desired database and viewpoint information. FIGURE 11 is a schematic diagram showing system 90 having a plurality of lenslet pixel modules 70 wherein each high resolution 2D source 78 preferably includes a respective internal CPU (not expressly shown), a communications adapter (not expressly shown) and associated video display circuitry (not expressly shown)along with the desired data base and viewpoint information. Master CPU 94 provides the desired digital data input to each lenslet pixel module 70. Consumer video game player systems which are available in compact sizes and at relatively low cost may be the basis for the electronic circuits and components for lenslet pixel modules 70. The benefits of this massively parallel computer

processing approach would be in distribution of the computation load, relaxation of signal distribution requirements, and greatly simplified connectivity as shown in FIGURE 11.

LENSLET PIXEL MODULES WITH SENSORS OR DETECTORS

Inclusion of a sensor or detector responsive to electromagnetic radiation from a real 3D object or scene within one or more lenslet pixel modules 70 will open up many interesting capabilities and uses for the associated full-parallax 3D display. As discussed later with respect to FIGURE 12, a CCD sensor or a miniature video camera may be incorporated into a lenslet pixel module having a partially silvered mirror and additional optics to virtually superimpose a 3D output image and a 2D sensor array. A consequence of this approach may be output brightness attenuation. Also, possibly increased bulk of the CCD sensor may require pixel module engineering to optimize lenslet pixel module packing density.

The integration of a 2D sensor array into a 3D electronic display in accordance with teachings of the present invention will allow full-parallax 3D image information of real 3D objects, scenes, and people to be easily acquired. This rich level of 3D data has many potential military and civilian applications such as object measurement, virtual reality simulation source

imagery, medical diagnostic information acquisition, and damage assessment information to name a few. Because the information could be acquired as moving images in real-time, the 3D data could be used as the basis for virtual-reality computer-human interaction. For example, multiple human observers could have simulated computer-graphic objects tracking their moving bodies in real time. Perhaps some observers could have their images appear on the associated 3D display in real time, while other observers choose to remain invisible.

Figure 12 is a schematic drawing showing lenslet pixel module 170 with projection element 78 and sensor element 172 combined in accordance with teachings of the present invention. Lenslet pixel module 170 preferably includes both high resolution 2D image source 78 and sensor element or detector element 172. Partially silvered mirror 176 is preferably provided to optically couple both high resolution 2D image source 78 and sensor element 172 with lenslet 74. A wide variety of sensors or detectors which respond to electromagnetic radiation from a real 3D object or scene may be satisfactorily used as sensor element 172.

For some applications high resolution 2D image source 78 may be coupled with a source of moving video images. Sensor element 172 may be coupled with an appropriate recorder or a computer processing unit to record images corresponding with one or more real 3D

objects (not expressly shown) disposed in front of lenslet 74.

Figure 13 is a schematic drawing showing various portions of system 180 which may be satisfactorily used to form an autostereoscopic image in accordance with teachings of the present invention. System 180 preferably includes a plurality of lenslet pixel modules 70 and a plurality of lenslet pixel modules 170. For purposes of describing various features of the present invention lenslet pixel modules 70 may also be referred to as projector modules. Lenslet pixel modules 170 may be described as combined projector/sensor modules. Master CPU 94 is preferably provided to communicate digital data corresponding with a desired 2D image to both lenslet pixel modules 70 and lenslet pixel modules 170. Master CPU 94 is also preferably operable to receive digital information from lenslet pixel modules 170 which correspond with one or more objects disposed in front of the associated lenslets 74.

For some applications, system 180 may be formed from a plurality of lenslet pixel modules 70 having associated high resolution 2D image sources 78 or projector elements 78 and a plurality of lenslet pixel modules or sensor modules having only associated sensor elements. One example of such sensor modules (not expressly shown) may be formed by replacing projector element 78 of lenslet pixel module 70 as shown in FIGURE 9 with a desired

sensor or detector element. System 180 may be satisfactorily formed with multiple projector modules, sensor modules and/or combined projector and sensor modules.

FIGURE 14 is a schematic drawing showing system 190 which may be used to form an interactive autostereoscopic display in accordance with teachings of the present invention. System 190 preferably includes master CPU 94 coupled with a plurality of lenslet pixel modules 170. For this embodiment the resulting 3D array includes a plurality of lenslet pixel modules 170 having both a projector element or (high resolution 2D image source 78) and sensor element 172. FIGURE 15 is a schematic drawing showing system 200 which may be used to form an interaction autostereoscopic display in accordance with teachings of the present invention. System 200 preferably includes master CPU 94 and a plurality of lenslet pixel modules 70 and 170. In addition, system 200 also preferably includes a plurality of lenslet pixel modules 70a which have a low resolution 2D image source (not expressly shown) and a plurality of sensor of lenslet sensor modules 170a which preferably include a low resolution sensor (not expressly shown).

Various features of the present invention have been described with respect to fly's eye lenslet sheet 52, associated lenslets 54 and fly's eye lenslet 74. However, it is well known in the art that a wide variety

lens sheets and lenses may be satisfactorily used to form 3D autostereoscopic images. Lens sheets and lenslets satisfactory for use in forming 3D electronic displays in accordance with teachings of the present invention may be fabricated using refractive methods or diffractive methods. A wide variety of lens sheets having a suitable lens array formed on a first surface and a second generally smooth flat surface disposed opposite from the first surface may be satisfactorily used to form lenslet pixel modules in accordance with the teachings of the present invention. The lenslets may be cylindrical, convex, concave, gradient index, diffractive, refractive, holographic optical elements or any other suitable prism which will form a full parallax 3D image.

For some 3D displays a plurality of sensors or detectors (not expressly shown) may be dispersed within an array lenslet pixel modules having only projector elements. The lenslet pixel modules may cooperate with each other to form a projector array. The sensor elements may also cooperate with each other to form a sensor array. The lenslet pixel modules and each sensor may include a fly's eye lenslet. For some applications, the sensor array may have a focal plane which corresponds approximately with a focal plane associated with the projector array. For other applications the sensor array may have a focal plane oriented substantially different from the focal plane of the projector array. For still

other applications one or more of the sensors may have a lenslet with a configuration different from the projector array. Also, the lenslet pixel modules in the projector array may have different lenslets. The sensor array may cooperate with the projector array to allow an observer to interact with a 3D image formed by the projector array.

The number of potential applications which could use a large 3D display incorporating teachings of the present invention is vast. It is expected that many people with virtual reality applications would be potentially interested in 3D electronic displays incorporating teachings of the present invention because of its unique aspects and capabilities. Some potential applications include mission planning, reconnaissance, damage assessment, scene analysis, education, training, simulations, mechanical and electrical engineering, cartography & terrain imaging, geoscience, seismic research, medical imagery, product design, architecture, space planning, advertising, scientific visualization and teleconferencing.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations may be made thereto without departing from the spirit and scope of the present invention as defined in the following claims.

WHAT IS CLAIMED IS:

1. Apparatus for displaying a three-dimensional image, comprising:

a plurality of lenslet pixel modules with each module defined in part by a respective lenslet;

each lenslet pixel module corresponding with a pixel of the three-dimensional image;

a plurality of two-dimensional moving image sources associated with and forming a portion of the lenslet pixel modules; and

the lenslet pixel modules cooperating with each other to form a projector array for displaying the three-dimensional image.

2. The apparatus of Claim 1 further comprising a fly's eye lens sheet having a plurality of fly's eye lenslets disposed thereon to provide the respective lenslet for each lenslet pixel module.

3. The apparatus of Claim 1 further comprising at least one lenslet pixel module having a partially silvered mirror and a sensor disposed adjacent thereto.

4. The apparatus of Claim 1 further comprising at least one lenslet pixel module having a high resolution two-dimensional digital image source associated with and forming a portion of the at least one lenslet pixel module.

5. The apparatus of Claim 1 further comprising:

the plurality of lenslet pixel modules disposed in an array relative to each other;

at least two of the lenslet pixel modules having a respective sensor disposed therein;

the sensors cooperating with each other to form a sensor array having a first focal plane;

the plurality of fly's eye lenslets associated with the lenslet pixel modules cooperating with each other to form a projector array having a second focal plane; and

the focal plane of the sensor array corresponding generally with the focal plane of the projector array.

6. The apparatus of Claim 5 wherein at least one sensor comprises a video sensor.

7. The apparatus of Claim 5 wherein at least one sensor comprises a charge coupled device.

8. The apparatus of Claim 1 wherein the three-dimensional image is full parallax.

9. The apparatus of Claim 1 further comprising:

the plurality of lenslet pixel modules disposed in an array relative to each other;

at least two of the lenslet pixel modules having a respective sensor disposed therein; and

the sensors cooperating with each other to form a sensor array for sensing at least one real three-dimensional object.

10. The apparatus of Claim 9 further comprising a central processing unit operable to receive information from the sensor array and to provide information to the projector array to allow interaction between the at least one real three-dimensional object and the three-dimensional image.

11. The apparatus of Claim 1 further comprising the high resolution two-dimensional image source selected from the group consisting of a cathode ray tube, a liquid crystal display, digital micro device mirror, a flat panel display, a respective section of a diffuser backlit by a video projection system, a microelectronicmechanical system, or a light emitting diode.

12. The apparatus of Claim 1 further comprising:

the plurality of lenslet pixel modules disposed in an array relative to each other; and

a high resolution two-dimensional image source associated with each respective lenslet pixel module.

13. The apparatus of Claim 1 further comprising:

the plurality of lenslet pixel modules disposed in an array relative to each other;

a two-dimensional high resolution image source associated with two or more lenslet pixel modules; and

each of the lenslet pixel modules associated with a dedicated region of the respective high resolution two-dimensional image source.

14. The apparatus of Claim 1 further comprising:

the plurality of lenslet pixel modules disposed in an array relative to each other;

a plurality of sensors interspersed within the array of lenslet pixel modules;

the sensors cooperating with each other to form a sensor array having a first focal plane; and

the lenslet pixel modules cooperating with each other to form a projector array having a second focal plane.

15. The apparatus Claim 14 further comprising the focal plane of the sensor array corresponding generally with the focal plane of the projector array.

16. The apparatus of Claim 14 further comprising the focal plane of the sensor array having an orientation different from the focal plane of the projector array.

17. A system for presenting a scalable, autostereoscopic image comprising:

a plurality of lenslet pixel modules with each module defined in part by a respective lenslet;

each lenslet pixel module corresponding with a 3D pixel of the autostereoscopic image;

a plurality of two-dimensional image sources associated with and forming a portion of each lenslet pixel module; and

at least one computer processing unit providing an input to the two-dimensional high resolution image sources.

18. The system of Claim 17 wherein the input supplied to the two-dimensional image sources comprises digital data corresponding to a two- dimensional image.

19. The system of Claim 17 wherein the input supplied to the two-dimensional image source comprises a moving video image.

20. The system of Claim 17 wherein the autostereoscopic image is full parallax.

21. The system of Claim 17 further comprising:

a plurality of first computer processing units having at least one video output channel to supply video images to the high resolution two-dimensional image sources;

two-dimensional image source coupled with one of the first computer processing units; and

a master computer processing unit coupled with and supplying data to the first computer processing units.

22. The system of Claim 17 further comprising:

a plurality of sensors with each sensor disposed within one of the lenslet pixel modules; and

each sensor coupled with the computer processing unit to provide information to the computer processing unit concerning a real object in front of the lenslet pixel modules.

23. The system of Claim 17 wherein the lenslets further comprise a plurality of lens selected from the group consisting of cylindrical, convex, concave, gradient index, diffractive, refractive, holographic optical elements and other prisms which form an autostereoscopic image.

24. The system of Claim 17 further comprising:

a plurality of sensors with each sensor coupled with the computer processing unit to provide information to the computer processing unit concerning a real object in front of the lenslet pixel modules;

a portion of the sensors providing high resolution information about the real object; and

a portion of the sensors providing low resolution information about the real object.

25. A method for presenting an autostereoscopic image comprising:

combining a plurality of high resolution two-dimensional digital image sources with a plurality of lenslet pixel modules with each pixel module having a respective fly's eye lenslet; and

projecting light from each digital image source through the respective lenslet pixel module to form the autostereoscopic image.

26. The method of Claim 25 further comprising installing at least two sensors within respective lenslet pixel modules for use in sensing at least one real object disposed in front of the lenslet pixel modules.

27. The method of Claim 25 further comprising:

sensing at least one real object disposed in front of the lenslet pixel modules with the sensors; and

combining information received from the sensors concerning the at least one real object with information supplied to the high resolution two-dimensional image sources to allow interaction between the at least one real object and the full-parallax autostereoscopic image produced by the lenslet pixel modules.

28. The method of Claim 25 wherein the autostereoscopic image is full parallax.

29. A lenslet pixel module for projecting light and sensing light comprising:

a two-dimensional image source operably coupled with a respective lenslet whereby a portion of a selected two-dimensional image may be projected from the lenslet to form a portion of an image;

a sensor disposed within and forming a portion of the lenslet pixel module; and

the sensor operably coupled with the fly's eye lenslet to allow the sensor to detect at least one real object in front of the lenslet pixel module.

30. The lenslet pixel module of Claim 29 wherein the sensor further comprises a digital video camera.

31. The lenslet pixel module of Claim 29 further comprising a portion of a full parallax three-dimensional electronic display.

32. The lenslet pixel module of Claim 29 further comprising the two-dimensional image source operable to form a portion of the image and the sensor operable to detect electromagnetic radiation from the at least one real object at substantially the same time.

DYNAMIC SCALABLE FULL-PARALLAX
THREE-DIMENSIONAL ELECTRONIC DISPLAY

ABSTRACT OF THE DISCLOSURE

A system and method are provided to form a large scale full-parallax three-dimensional electronic display. Multiple lenslet pixel modules are preferably formed by combining a high resolution two-dimensional image sources with respective lenslets. For some applications each pixel module has a respective two-dimensional high resolution image source. For other applications two or more lenslet pixel modules may use respective portions of the same high resolution two-dimensional image source. One or more computer processing units may be used to provide video images or graphical image data to the high resolution two-dimensional image sources. For some electronic displays, the lenslet pixel modules form an array of projectors and an array of sensors may be disposed within the array of projectors. The array of sensors may cooperate with the array of projectors to allow interaction between one or more observers and a three-dimensional image produced by the projector array.

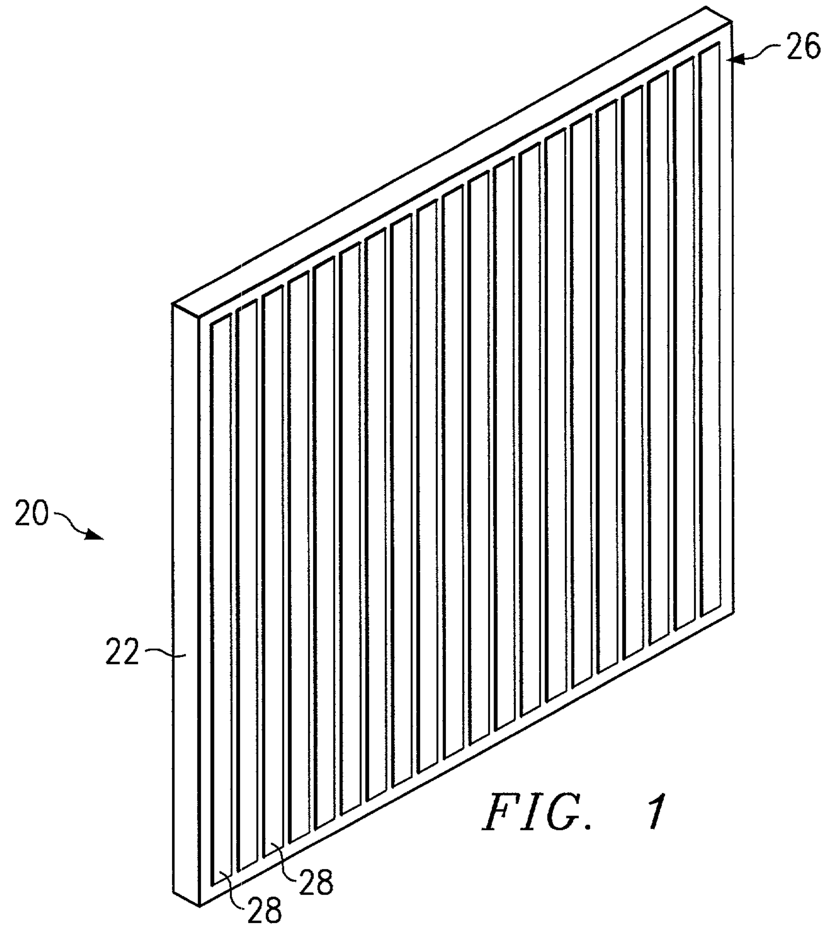

26
20
22
28
28

FIG. 1

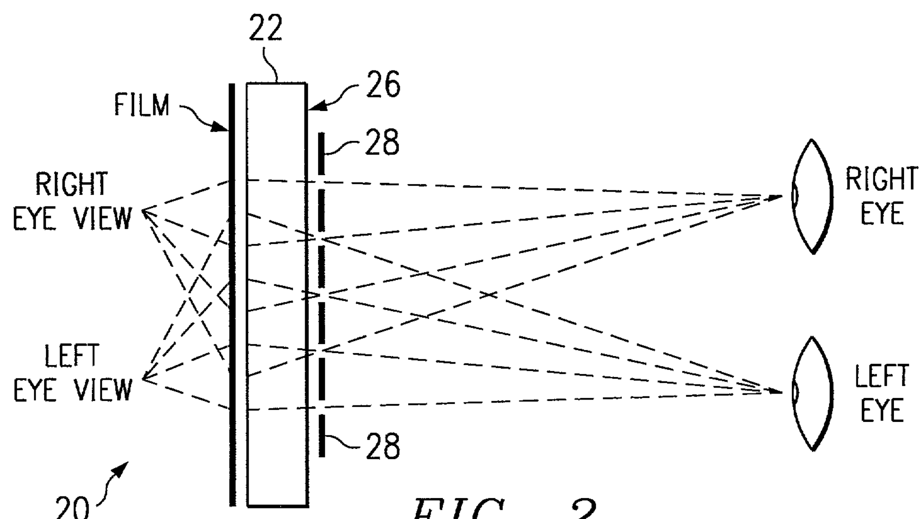

22
FILM
26
28
RIGHT EYE VIEW
LEFT EYE VIEW
RIGHT EYE
LEFT EYE
28
20

FIG. 2

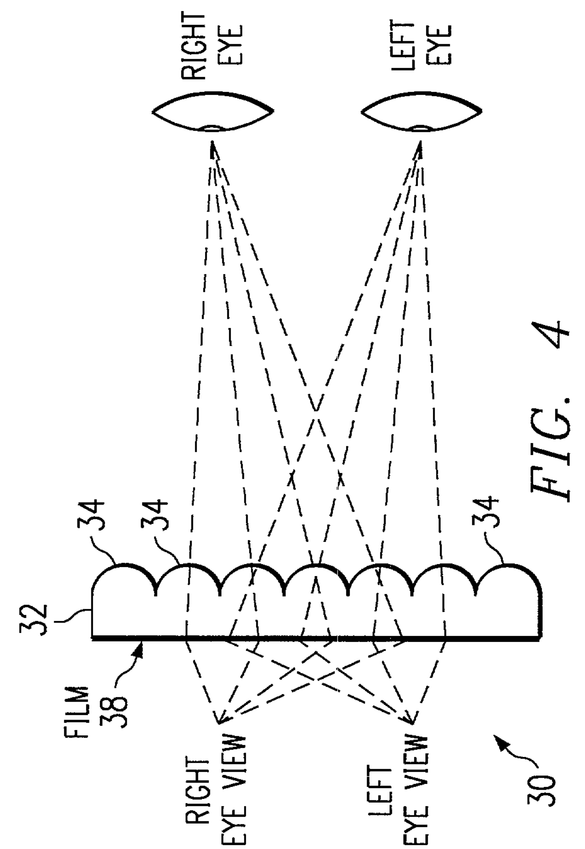


FIG. 4

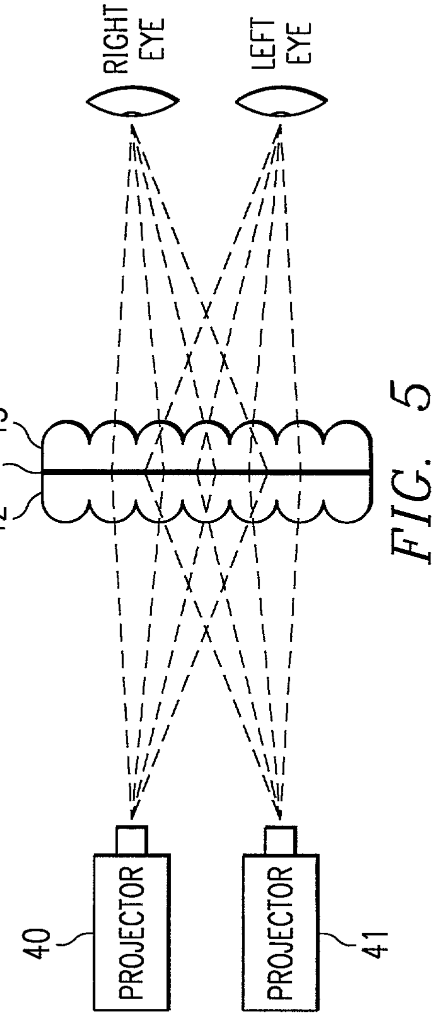


FIG. 5

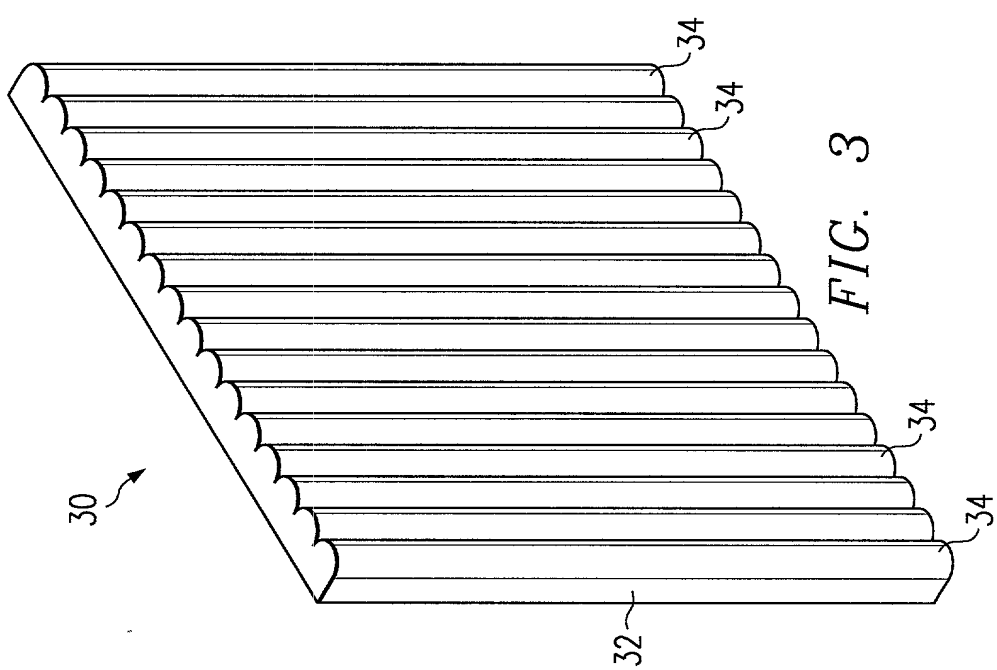


FIG. 3

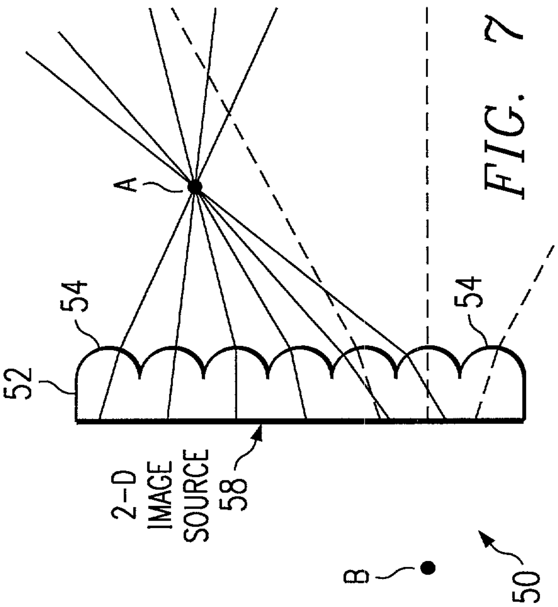


FIG. 7

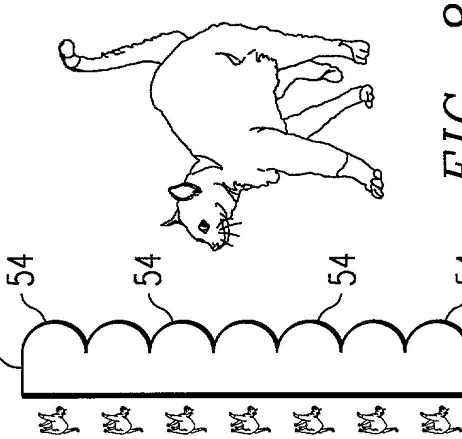


FIG. 8

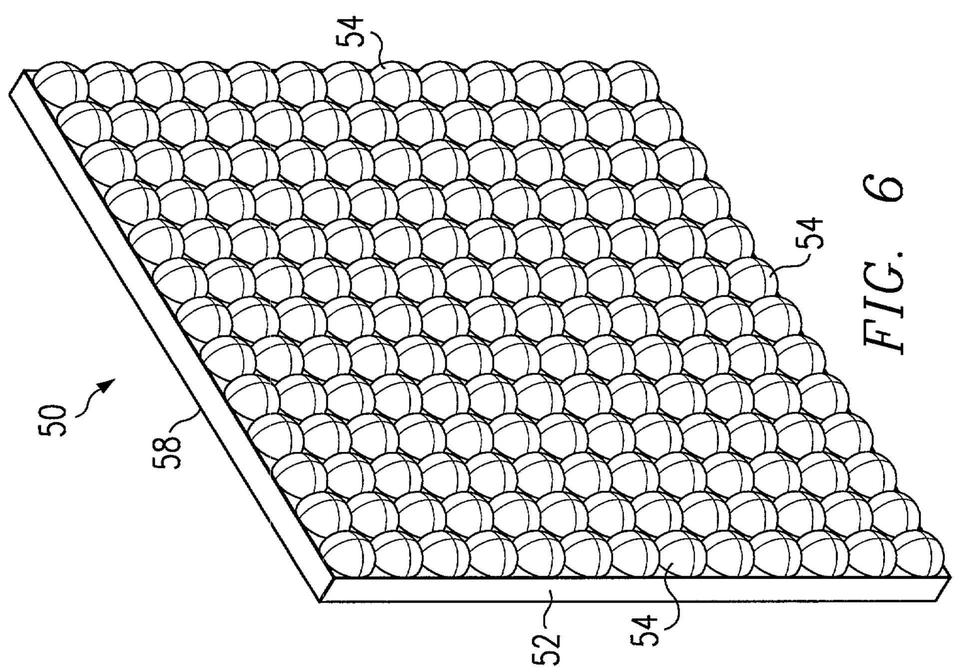


FIG. 6

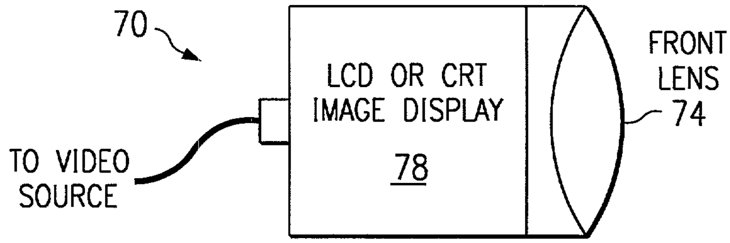


FIG. 9

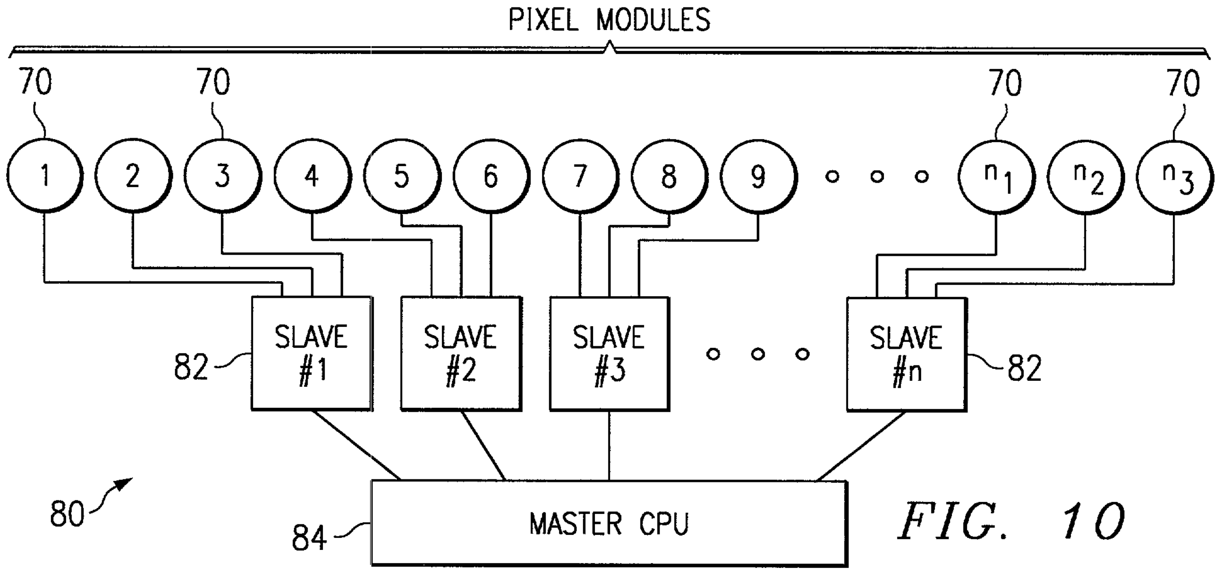


FIG. 10

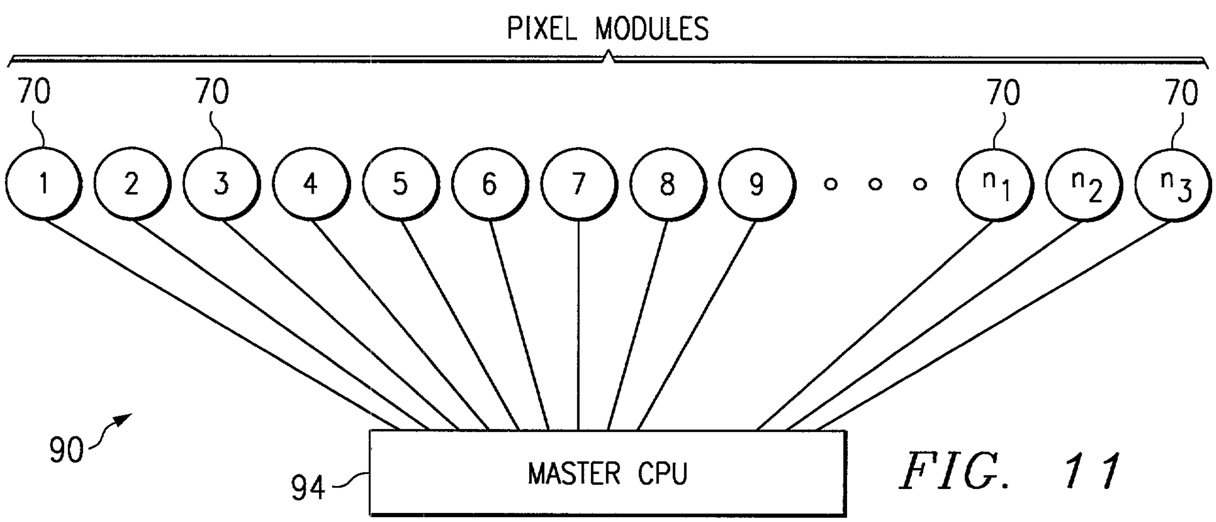


FIG. 11

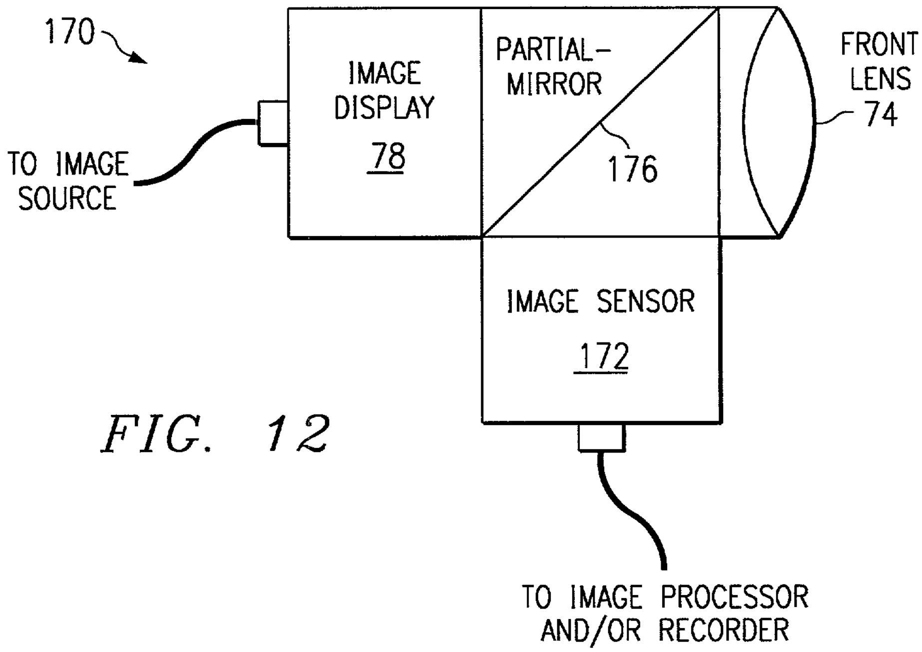

170
IMAGE DISPLAY
78
PARTIAL-MIRROR
176
FRONT LENS
74
TO IMAGE SOURCE
IMAGE SENSOR
172
TO IMAGE PROCESSOR AND/OR RECORDER

FIG. 12

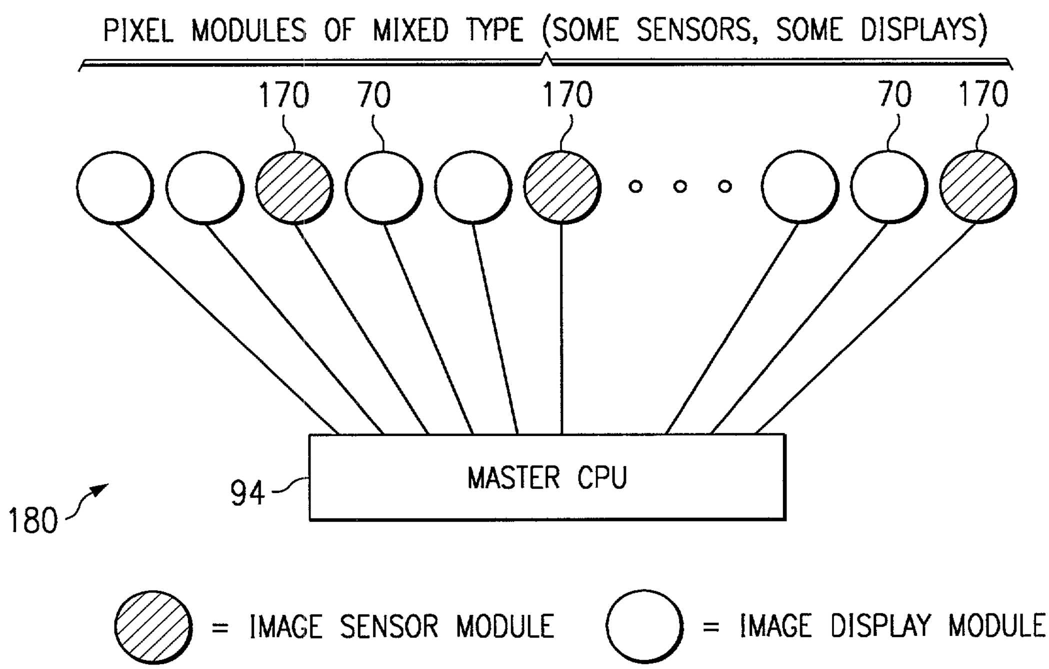

PIXEL MODULES OF MIXED TYPE (SOME SENSORS, SOME DISPLAYS)
170
70
170
70
170
MASTER CPU
94
180
= IMAGE SENSOR MODULE
= IMAGE DISPLAY MODULE

FIG. 13

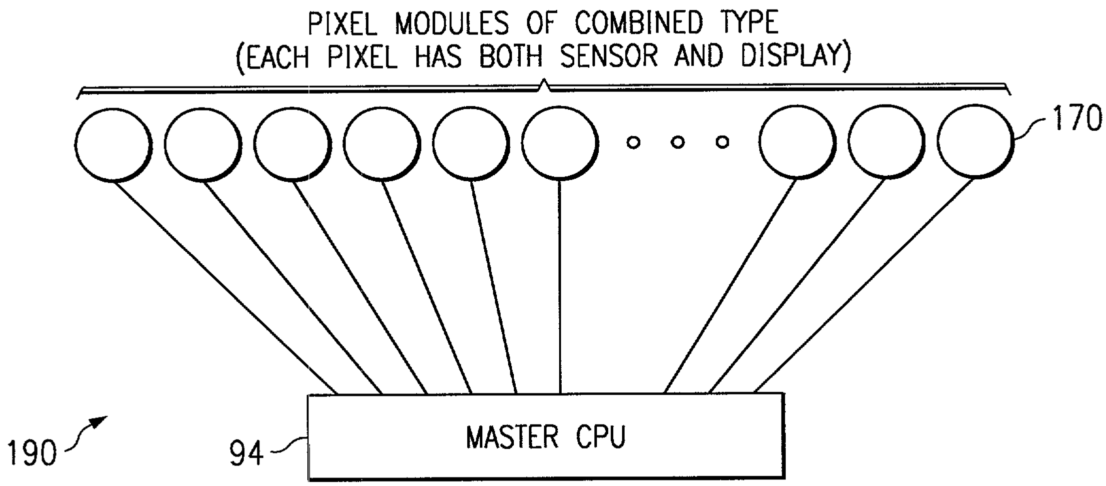

PIXEL MODULES OF COMBINED TYPE
(EACH PIXEL HAS BOTH SENSOR AND DISPLAY)
170
190
94
MASTER CPU

FIG. 14

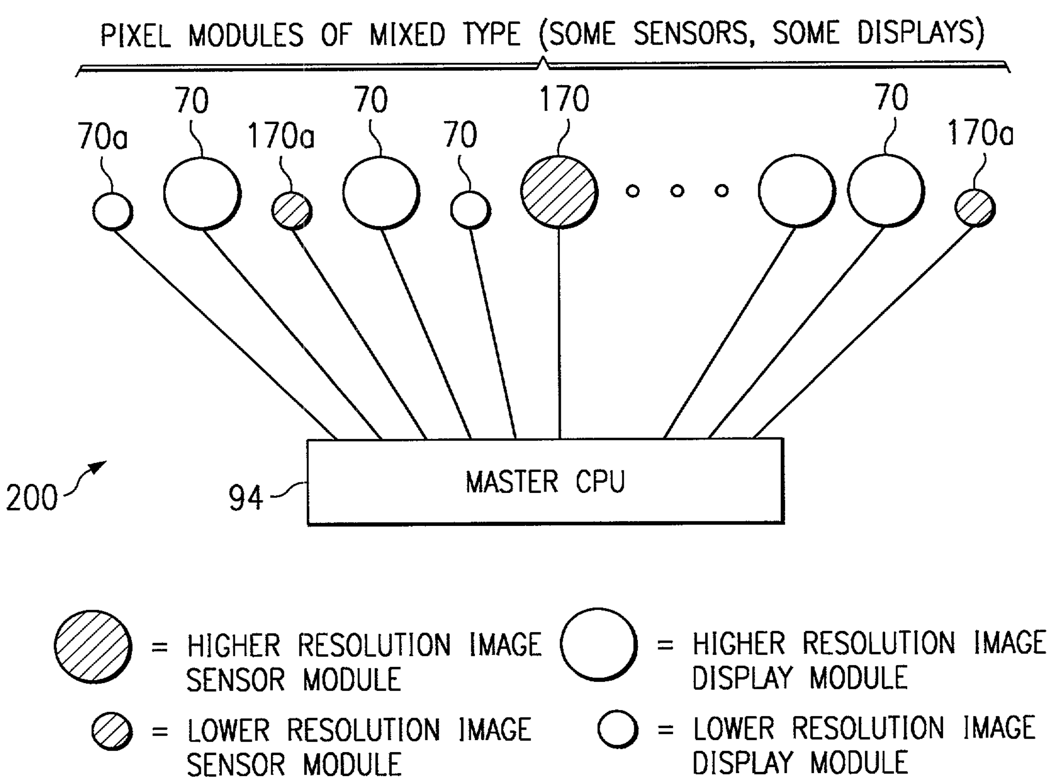

PIXEL MODULES OF MIXED TYPE (SOME SENSORS, SOME DISPLAYS)
70a
70
170a
70
70
170
70
170a
200
94
MASTER CPU
= HIGHER RESOLUTION IMAGE SENSOR MODULE
= HIGHER RESOLUTION IMAGE DISPLAY MODULE
= LOWER RESOLUTION IMAGE SENSOR MODULE
= LOWER RESOLUTION IMAGE DISPLAY MODULE

FIG. 15

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I declare that:

My residence, post office address and citizenship are as stated below next to my name, that I believe I am the original, first and joint inventor of the subject matter which is claimed and for which a patent is sought on the invention or design entitled **DYNAMIC SCALABLE FULL-PARALLAX THREE-DIMENSIONAL ELECTRONIC DISPLAY**, the specification of which is attached hereto.

That I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above; and that I acknowledge the duty to disclose to the U.S. Patent and Trademark Office all information known to me to be material to patentability as defined in 37 C.F.R. § 1.56.

I hereby claim foreign priority benefits under 35 U.S.C. § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application(s) for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Number	Country	Date Filed	Priority Claimed (Yes) (No)

None.

I hereby claim the benefit under 35 U.S.C. § 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is

not disclosed in the prior United States application(s) in the manner provided by the first paragraph of 35 U.S.C. § 112, I acknowledge the duty to disclose to the U.S. Patent and Trademark Office all information known to me to be material to patentability as defined in 37 C.F.R. § 1.56 which became available between the filing date of the prior application(s) and the national or PCT international filing date of this application:

Application Serial Number	Date Filed	Status
None.		

I hereby claim the benefit under Title 35, United States Code, § 119(e) of United States provisional application number 60/111,906 filed December 10, 1998 and entitled "Dynamic Scalable Full-Parallax Three-Dimensional Electronic Display"

I hereby appoint:

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T. Murray Smith	Reg. No. 30,222
Barton E. Showalter	Reg. No. 38,302
David G. Wille	Reg. No. 38,363
Bradley P. Williams	Reg. No. 40,227
Terry J. Stalford	Reg. No. 39,522
Christopher W. Kennerly	Reg. No. 40,675
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James J. Maune	Reg. No. 26,946

Roger J. Fulghum	Reg. No. 39,678
Rodger L. Tate	Reg. No. 27,399
Scott F. Partridge	Reg. No. 28,142
James B. Arpin	Reg. No. 33,470
James Remenick	Reg. No. 36,902
Jay B. Johnson	Reg. No. 38,193
Robert W. Holland	Reg. No. 40,020
Floyd B. Chapman	Reg. No. 40,555
Randall W. Mishler	Reg. No. 42,006
Robert A. King	Reg. No. 42,738
James L. Baudino	Reg. No. 43,486
Scott T. Morris	Reg. No. 43,818
Tara D. Knapp	Reg. No. 43,723
William B. Borchers	Reg. No. 44,549
Robin A. Brooks	Reg. No. 44,563
Darren W. Collins	Reg. No. 44,625
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all of the firm of Baker & Botts, L.L.P., my attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the United States Patent and Trademark Office connected therewith, and to file and prosecute any international patent applications filed thereon before any international authorities.

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I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false

statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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